MACAULAY LAND USE RESEARCH INSTITUTE

ANNUAL REPORT 1997

Macaulay Land Use Research Institute

Craigiebuckler Aberdeen

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1997

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DIRECTOR'S INTRODUCTION

From a European perspective, our research is set in the context of the policy objectives for agricultural, environmental and rural development as indicated in the reform of the Common Agricultural Policy, the 5th Environment Programme and the emerging measures to stimulate rural development under the reform of the structural funds (e.g., Agenda 2000). The requirement is to increase the market orientation of agriculture whilst minimising its impact on the environment and maintaining rural economies. In consequence our research takes account of the needs of those organisations which deal with the impact of land use on the environment, including aquatic ecosystems (e.g., in Scotland, SNH, SEPA, the water industry and voluntary environmental bodies). We undertake, therefore, basic and strategic research that provides a clearer understanding of rural ecosystems and which underpins the applied-strategic research in developing different options for land use involving agriculture, forestry, conservation of the natural heritage, recreation and tourism. Our research also provides a basis for critically evaluating the consequence of different land uses for rural development, catchment management, rural socio-economics and the environment as a whole.

The thematic structure of our programme of research is based on the concept of the sustainable use and management of land. Its overall aim is to meet the needs of land managers and those formulating and implementing land use policy in Scotland, the UK, Europe and where appropriate, elsewhere internationally. The focus of our programme is unequivocally set within the context of the UK Government's commitment to sustainable development and the Scottish Office commitment 'Towards a Development Strategy for Rural Scotland'. Our approach is to gain knowledge and understanding about processes and mechanisms, to use such knowledge in systems synthesis, to investigate technical options for land use and its management, and study their impact on natural resources, people and the economy. Our adoption of a systems approach to research is fundamental in developing a true understanding of sustainability. Within and across each of the programme areas we have a combination of skills and research approaches which support systems synthesis as well as reductive and inductive science. We believe that the key to achieving effective sustainable management is to find ways of incorporating and linking models, containing a wide range of processes and mechanisms, to other information represented in knowledge-based systems in the construction of decision support tools. This requires a multidisciplinary and integrated research approach.

Consequently, since April 1997 our programme of research has been undertaken within four major themes, *viz* Sustainable Integrated Land Use Options, Integrated Catchment Management, Sustainable Management of Soils, and Sustainable Management of Marginal Lands. Within these themes the programme is managed as a series of mission oriented programmes. The first theme, **Sustainable Integrated Land Use Options**, comprises two programmes, ***Geographical and Resource Analysis and Socio-Economic and Policy Analysis.*** The first of these programmes provides the underpinning strategic research required to support and develop land use options and environmental audit analyses. In particular it addresses the handling of error and uncertainty in spatial data analyses, and creates appropriate frameworks to develop biophysical and decision support tools within a spatial domain. Information from other programmes is incorporated into land use models for assessing the impacts of land use options at various scales ranging from the farm, the district, the region to the catchment.

The ***Socio-Economic and Policy Analysis*** programme focuses its research in the area of environmental economics and management within an overall context of rural change and development, dealing specifically with spatial economic analysis, economic evaluation of environmental change, and rural sustainability. The aim is to provide environmental and agri-environmental policy analysis with a biophysical base for predicting policy impacts. It is therefore linked to the applied research components of other programmes.

The second theme, **Integrated Catchment Management**, involves one programme, ***Atmospheric Deposition, Land Use and Water Quality Management.*** This programme addresses the consequences of the fact that land in much of Europe is affected by atmospheric deposition arising from sulphurous and nitrous emissions from urban industry and transport, and that there is a pollution impact from agriculture and forestry on water bodies and river catchments, in particular, with respect to nitrogen and phosphorus.

The third theme, **Sustainable Management of Soils**, is being developed within one programme, ***Soil Quality, Contaminated Land and Waste Utilisation.*** This programme addresses issues related to the functionality of soils under different land uses and/or subject to pollution with specific reference to their physical, hydrological and microbiological status. It aims to provide strategic information on the content, behaviour, impact and fate of a range of contaminants in soils relevant to Scotland, Europe and elsewhere.

The fourth theme, **Sustainable Management of Marginal Lands**, includes four programmes, ***Land Use Options for Plants; Natural Heritage Management - Vegetation Dynamics; Natural Heritage Management - Herbivore Foraging; and Land Use Options for Animals.*** These programmes deal predominantly, but not exclusively, with the major uses of, and interests in, land characterised by soils of low pH, high organic matter and low fertility, and natural and semi-natural vegetation.

The ***Land Use Options for Plants*** programme is concerned with the impact of nutrient supply on the processes of carbon and nutrient assimilation and partition in trees and grasses. It provides the underpinning strategic information for the management of plants adapted to low fertility soil environments and relates closely to the programme on Vegetation Dynamics and the land and environmental management components of the Sustainable Integrated Land Use Options programme.

The ***Vegetation Dynamics and Herbivore Foraging*** programmes are concerned with understanding and predicting the impacts of large herbivores, such as sheep, cattle and red deer, on semi-natural vegetation (including woodland, heath and extensively managed grassland) on the one hand, and understanding how these domestic and wild herbivores behave and forage in these heterogeneous ecosystems, on the other. The technology transfer from these programmes are through the development of decision support tools. These aim to predict the impact of grazing on vegetation dynamics, animal production and population dynamics.

The aim of the ***Land Use Options for Animals*** programme is to identify relevant options for land use by ruminants and to investigate their biological properties. The research focuses on grazing systems, animal fibre production and animal welfare.

There are also three integrated research programmes. The overall strategy is to manage these programmes to contribute, and either underpin or add value, to the research undertaken within the mission-oriented programmes. Not only do they provide a management framework and set of unifying objectives to meet the needs of an integrated research topic, but they also provide a co-ordinating framework for work being undertaken at specific levels of biological organisation and physical scale (see Figure 1).

The integrated programme, ***Soil-Plant-Animal Interactions*** addresses issues of strategic importance related to the interaction between the biophysical components of the soil, plants and animals which are fundamental to a holistic view of land use options, their management, and their impact on the environment. Initially, this programme is focusing on processes regulating the dynamics of nitrogen and phosphorus and their availability in the rhizosphere for their uptake by plants and microbes, and the effects of rhizosphere carbon flow and the impact of animal excretal returns on soil microbial activity and rhizosphere nutrient dynamics.

The integrated programme, ***Long-term Measurement and Monitoring of Change***, contributes to a continued assessment of the anthropogenic impact on the environment. In this context the measurement of change in environmental parameters is of central importance and is reflected in several UK initiatives, such as the Environmental Change Network, the Royal Commission on the Environment Report and the measurement of Land Cover Change. Specifically, this programme is focusing on methods of measurement of change at varying scales, is developing novel sampling strategies to improve the characterisation of change at boundaries of land cover features and is exploring the concept of habitat condition assessment.

The integrated programme, ***Development of Decision Support Systems***, is developing an infrastructural framework to facilitate and co-ordinate the development of decision support systems as output from the programmes within the four research themes. Specifically, and initially, this programme is creating derived weather/climate and soil data sets appropriate to a number of applications, and the development of suitable generic user interfaces to facilitate the inter-changeability of sub-models which make up decision support systems.

Last year the Annual Report was based on the themes that provide the context for our programmes of research. This year the articles that follow provide a more detailed account of the work being undertaken in each of the programmes and the progress that is being made in achieving their objectives. I am confident that those who have an interest in any aspect of rural land use will find the ideas, information and opportunities emerging from our research to be at the forefront of knowledge, understanding and thinking on the issues that are central to the sustainable management and use of rural resources.

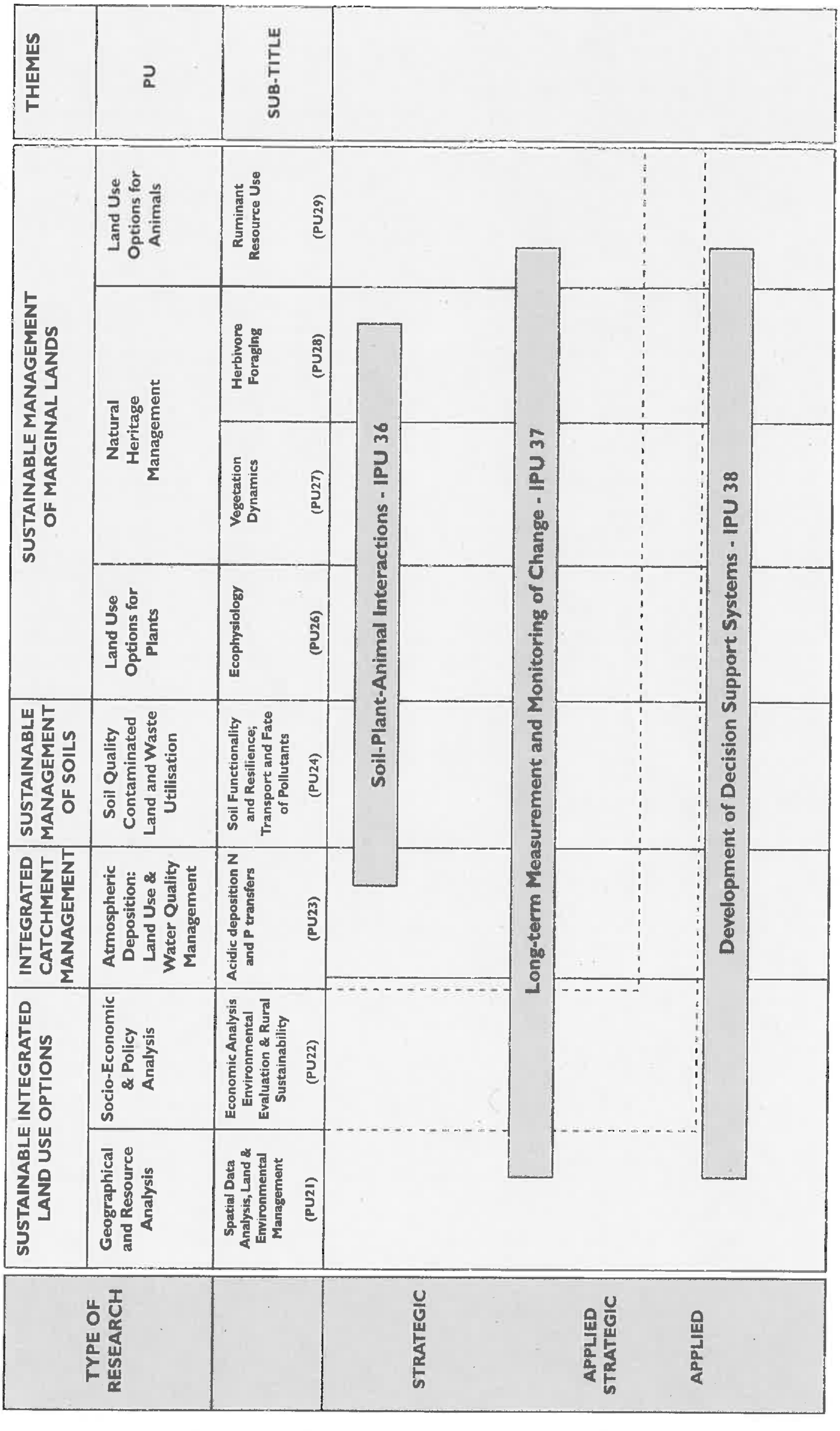
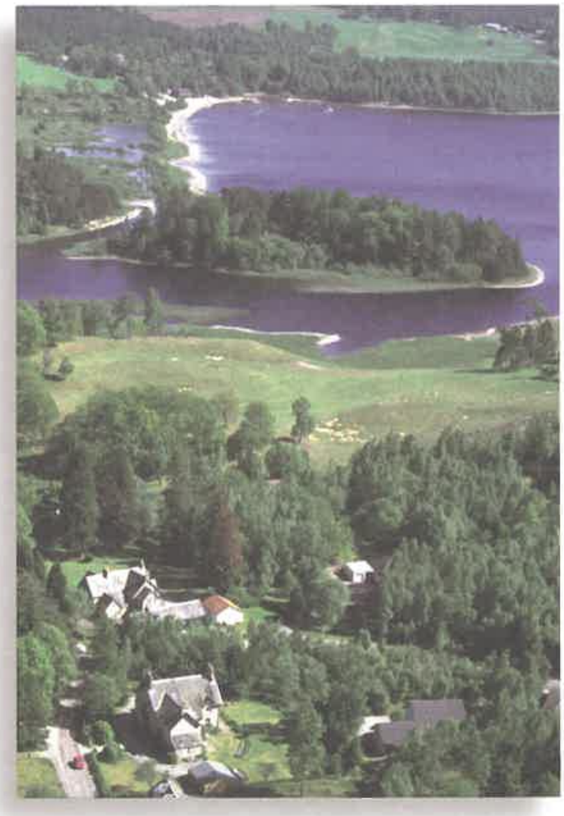


Figure 1. MLURI Programme of Research.

CONTENTS



This research programme aims to develop and apply new concepts and methods for analysing land resources, for assessing integrated land use options and for predicting land use changes.

Geographical and Resource Analysis

The Geographical and Resource Analysis Programme takes a wider view of land use activities and their effects on the rural environment (Maxwell, 1997). Developed in response to the need to define sustainable land use systems which deliver social, economic and environmental benefits, the programme aims to develop and apply new concepts and methods for:

- **analysing land resources**
- **assessing integrated land use options**
- **predicting land use changes**

Currently our research is focused on two geographic scales: management unit and region. The main customers for this research are land managers/advisors, and land use policy advisors respectively. The principal means of technology transfer are through the development of decision support tools, involvement with participatory user groups, and the provision of consultancy services.

Our research approach is a multi-disciplinary one, and is based upon concepts derived from geographical science, systems research and complex systems theory. Our methods utilise advanced computing technologies drawn primarily from the computing science domains of Geographic Information Systems (GIS), expert systems, artificial intelligence and artificial life. We aim to provide new insights into land use science issues both at strategic and applied levels. Where appropriate, we link to international centres developing complementary expertise including, for example: the National Centre for Geographic Information and Analysis (NCGIA) and Santa Fe Institute in the United States; the Commonwealth Industrial and Scientific Research Organisation (CSIRO) in Australia; Landcare and AgResearch in New Zealand; Institut National de la Recherche Agronomique (INRA) in France and the Winand Staring Centre in Holland.

What factors determine our ability to assess the 'sustainability' of land use options? Firstly, we recognise that sustainable land use systems provide a wide range of goods and services. Some of these (e.g., food and fibre) are marketed and are easy to value. Others are not marketed (e.g., conservation, amenity, recreation, environment) and are difficult to value in monetary terms. Nonetheless, all these goods and services have costs and benefits in social, economic and environmental terms. Therefore a central problem in analysing the sustainability of alternative land use options is how to express and value the trade-offs being made between these different dimensions.

Two other factors are also important in assessing the sustainability of land use options. The first is that the 'costs' may not be felt in the same place as the 'benefits': a geographical effect. The second is that the 'costs' and 'benefits' are experienced by different groups in society in different ways: so there is no single value for 'cost' and no single value for 'benefit'. This is a societal effect and as a consequence the term 'sustainable' has no absolute definition. Its use reflects a spectrum of beliefs in our society. These range from the technocentric view of man winning over nature (Simon and Kahn, 1984), to the ecocentric view of man within nature (Schumacher, 1973). We have to be able to interpret our scientific results in the context of these different viewpoints.

A simple example of the geographical effect is acid rain, where the benefits of industrial activity in the U.K. have impacts on the fish stocks of lakes and rivers in southern Norway. More complex examples range from the incremental effects of agricultural runoff from individual farms on the nutrient levels in river systems like that of the River Ythan in northeast Scotland, to the cumulative impact of the loss of family farms on the viability of rural schools. These geographical effects are further confounded by time effects. It can take many years for a system to show signs of 'damage', and effects can persist long after the original cause has been removed (the Chernobyl accident provides a good example of this). Understanding these spatio-temporal effects and accounting for them in a cost-benefit analysis framework is one of the central challenges in sustainability assessment.

Examples of the societal effect are common. Nearly every land use issue in Scotland, from the Cairngorm funicular railway and windfarm developments, to public access to land, highlights the different valuation systems of the various stakeholding groups at work. Valuations are specific to individual stakeholder groups, and there is no 'right' answer. If our science is to be relevant and useful in resolving land use conflicts we must see it as part of a multi-stakeholder, consensus-building process, which scientists help enable and participate in.

Inspired by the work of management scientists like Checkland (1989) in the development of Soft Systems Methodologies, extension scientists, particularly those like Röling (1988) and Jiggins (Jiggins and de Zeevw, 1992) in the Department of Communication and Innovation Studies at Wageningen Agricultural University, have pioneered this participatory, co-learning approach, to the point where it is now a key element of modern rural development and extension practice. The benefits of the approach are exemplified by the success of many of the Landcare Groups in rural Australia (Campbell, 1994). Therefore, sustainability not only requires us to question the science that we do but also how we do it.

Leading from the above it is important that our methods should therefore:

- Depend on adequate characterisation and evaluation of biophysical potential of land resources at appropriate spatial scales (Holdgate, 1997);
- Reveal the trade-offs being made between market and non-market goods and services;
- Be capable of dealing with effects that may be non-linear and that may propagate off-site at different times into different spatial units and/or other elements of the socio-economy;
- Be accessible to different stakeholder groups so that they can explore options on the basis of their own perspectives and goals, and participate with others in developing consensus solutions.

Strategic Objectives

Our aim in the Geographical and Resource Analysis Programme Unit, (PU21) is to build decision support tools for exploring and understanding land use options. These are based on sound information about biophysical resources and their land use potentials; tools that operate in a dynamic and spatially explicit manner; and tools which are accessible i.e. built with the stake-holding groups rather than for them. The perspective of the programme is principally a biophysical one. This complements the socio-economic perspective of the Socio-Economic and Policy Analysis Programme (PU22), which also runs under the theme of Sustainable, Integrated Land Use Options. The programme links to the outputs from other programmes and specifically to the integrated programmes Long-term Measurement and Management of Change (IPU37) and Development of Decision Support Systems (IPU38).

The research is advanced through the Scottish Office Agriculture, Environment and Fisheries Department (SOAEFD) core-funded programme, related externally-funded research, mainly from the European Union, and from external consultancies. The outputs from the programme are principally: scientific papers, computer software and consultancy services.

We have three strongly inter-related core research activities (Figure 1). These are primarily applied at the management unit and regional geographical scales. Each

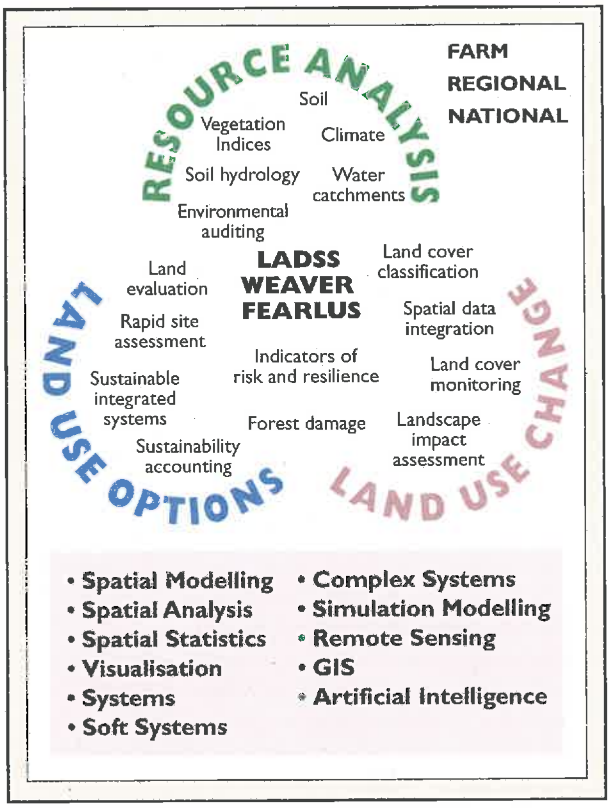


Figure 1. The core research activities of the Geographical and Resource Analysis Programme, (PU21) (resource analysis, land use options, land use change) and specific Information Technology/ analytical methods (bottom left) and topic areas (e.g., land cover monitoring). Note the central place of software developments like the Land Allocation Decision Support Systems (LADSS), WEAVER, and the Framework for Evaluation and Assessment of Regional Land Use Scenarios (FEARLUS).

activity is described separately below, in terms of our strategic and short term objectives, and our research achievements in 1996/97 relative to these. A selection of the research projects is presented to provide specific insights on the innovatory nature of our programme and its significance in both scientific and applied terms.

I) Land resource analysis

Objectives

Our strategic objective is to develop and apply novel remote sensing, spatial analysis and environmental modelling techniques to improve the characterisation of land resources, the assessment of land use potentials and the monitoring of land use/land cover change. Our short term objectives are to develop (new initiatives are in italics):

- Remote sensing technology for resource analysis at the field and regional scales (links to the Natural Heritage Management: Herbivore Foraging Programme PU28 and the Long-term Measurement and Monitoring of Change Integrated Programme IPU37).
- Automated land cover change detection (links to the Long-term Measurement and Monitoring of Change Integrated Programme IPU37).
- A spatio-temporal, biophysical resource modelling framework.
- Pedotransfer functions for soil hydrology related applications (links to the Atmospheric Deposition, Land Use and Water Quality Management Programme PU23).
- Models of physical impacts on landscape (links to the Socio-Economic and Policy Analysis Programme PU22).
- *Integrated resource data infrastructures* (links to the Development of Decision Support Systems Integrated Programme IPU38).

Internationally, there is an expressed need to maintain up to date information on land resources, primarily in support of the policy assessment, efficiency of land management and for State of Environment Reporting (UN Environment Programme). Particular initiatives in the United States, like the national Land Cover Characteristics Programme (LCCP) are being closely tracked. This effort is co-ordinated through the Multi-Resolution Land Characterisation consortium (MRLC) (Van Driel and Loveland, 1996) and it should be noted that MLURI initiatives to update the Scottish Office Land Cover of Scotland 1988 dataset are similar in objective. Further, at the NCGIA and USGS sponsored conference on Land Use Modelling (see http://www.ncgia.ucsb.edu/cont/landuse97), land cover and land use data were recognised as essential for the development and testing of land use models.

Achievements

(software developments in italics)

- Development of a method for assessing regional vegetation dynamics based upon analysis of time-series of meteorological satellite data (NOAA AVHRR). In collaboration with University of Dundee (Marcal and Wright, 1997).
- Proof of concept in relation to the integrated use of high resolution satellite data (LANDSAT TM) and the Heather Moorland Management Model (Wright, G G, Sibbald, A R and Allison, J S, 1997).
- *Creation of a knowledge-based system for monitoring land cover change called SYMOLAC. In collaboration with University of Aberdeen (Skelsey, 1996; 1997; see also: http://www.bamboo.mluri.sari.ac.uk/~chriss/Research Overview.html).*
- Critical assessment of 8 alternative methods of deriving slope from digital terrain models (Jones, in press).
- *Development of a European database called HYPRES, a unique source of soil hydrological, pedological and environmental data for the EU. In collaboration with a consortium of EU partners.*
- *Creation of WWW-based, integrated forest damage risk assessment DSS called STORMS. In collaboration with a consortium of UK and EU partners (see: http://www.bamboo.mluri.sari.ac.uk/aair/aair-home.html).*
- Fundamental research into landscape preference in collaboration with SNH and RGU (see http://www.mluri.sari.ac.uk/~mi550/home.html).

Current Research

A system for monitoring land cover (SYMOLAC)

The Institute completed the Land Cover of Scotland 1988 (LCS88) database on behalf of the Scottish Office in 1993 (MLURI, 1993). This is the first complete census of the land cover of Scotland. It is based upon interpretation of specially-flown aerial photography, recognises 126 land cover features and has a minimum mapping unit of between 2-10ha depending on land feature. The main purpose of the LCS88 database is to provide a baseline for monitoring change in the Scottish countryside.

Having developed the national baseline in the form of LCS88, the key challenge was to create a facility for monitoring changes. Although there is a growing international community with interests in land cover and cover change (e.g., International Geosphere/ Biosphere Programme and Human Dimensions Programme joint project on 'Land Use and Cover Change') there is no standard methodology for change detection. We recognised in particular, that whilst it was possible to simply repeat the LCS88 methodology, the relationship between the known rates of change in the Scottish countryside and the interpretation errors inherent in the methodology would lead to unacceptable results (i.e. it would be hard to tell whether changes were real or simply artefacts of the methodology). A more accurate method of change detection is required.

In response to this challenge we have been working on an alternative approach to monitoring land cover change. This is an automated approach based upon the coupling of image analysis, GIS and knowledge-based systems environments. This approach explicitly recognises the context of land cover changes as the consequence of interactions between real-world objects about which we have more knowledge than is represented in aerial photos or satellite images alone.

We have created a knowledge-based SYstem for MOnitoring LAnd Cover (SYMOLAC). This has been designed as a framework within which disparate knowledge and data can be applied to the problem of monitoring land cover. Gensym's G2 expert systems tool forms the central reasoning component of the system. This uses a blackboard-based problem-solving model to enable the concept of feature/location specific opportunistic reasoning based upon the interactions of a set of modular collections of expert knowledge. The decision whether or not to support an instance of change that might have been detected from comparison of images is therefore based upon the endorsement of the experts. A simple illustration of this is given in Figure 2 in relation to the hypothesis that an area of change represents an area of felled trees. A critical aspect of the SYMOLAC environment is that it links G2 to the ARCINFO GIS and PV-WAVE image analysis packages thus allowing third-party components to be used whenever an expert requires such functionality. This is a unique facility.

SYMOLAC is currently at the prototype stage. It has been applied to the relatively simple problem of detecting forest changes. For example, Figure 2 shows its application to a LANDSAT TM image from 1995 where LCS88 is used as part of the evidence in the change detection process. Having developed this task-oriented environment for detecting change, the next stage in its development will be to examine a much wider range of land cover types, their states and transitions. This work complements other research on the integration of remotely sensed satellite data with the LCS88 dataset (Wright and Morrice, 1997) and, in particular, the improvement of air-photo interpretation procedures. SYMOLAC and the other change detection research projects represent a significant investment not only to the creation of a land cover change database for Scotland but also a contribution to the international effort in developing change detection methodologies.

Further information on SYMOLAC can be found on: http://www.bamboo.mluri.sari.ac.uk/~chriss/Research Overview.html

Deriving slope estimates from Digital Elevation Models

Slope is a critical variable in many land use evaluations. The automated derivation of slope from digital contour maps or digital elevation models (DEMs) has been the subject of considerable international research particularly in Australia (Hutchison and Dowling, 1991) and the United States (Hodgson, 1995). Slope estimation algorithms have been incorporated in major GIS packages. However, there is no literature which establishes the relative strengths and weaknesses of the different estimation algorithms. Fundamental work has been undertaken within the MLURI group on the effectiveness of eight methods proposed in the literature for estimating slope from DEMs. These methods have been encoded and applied to both a synthetic and a 'real' landscape.

A trigonometrically defined surface was used as the synthetic surface. This was differentiated analytically to provide true slope and aspect values to act as a test set for comparing the performance of the estimation algorithms. The residual slope and aspect grids for each algorithm were used to calculate the error rates. These were subsequently used to rank the performance of each algorithm. This provides a rigorous basis for assessing the likely performance of algorithms implemented in a range of commercial GIS packages.

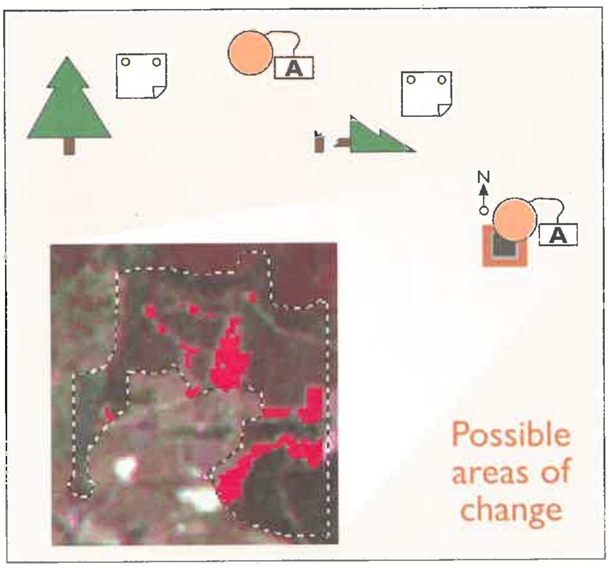


Figure 2. An area of change on the satellite image (LANDSAT TM) is checked by the SYMOLAC expert system to see whether the hypothesis that it is an area of felled trees is endorsed.

The results of the best performing algorithm on the synthetic surface were used as a reference for comparing the performance of other algorithms on a DEM in a mountainous area of Portugal. This part of the study was done in collaboration with the Portuguese National Centre for Geographic Information (CNIG) as part of the STORMS project. The context was the possible effects of error in slope estimates on the outputs of a fire risk assessment model (Fire Map). The results showed that the Fleming and Hoffer (1979) and Horn (1981) methods were best, whilst the maximum downward gradient method of Travis *et al.*, (1975) was the poorest (Jones, in press). The results also showed that where estimates of fire risk were particularly sensitive to slope (e.g., in v-shaped features like gullies), about 5% of the test area was assigned to the wrong fire risk classes. This research has clear relevance to the generic issues of error and uncertainty in spatial modelling.

The STORMS project

Forest damage by wind, snow and fire in Europe constitutes the most serious economic problem facing the forestry industry. For example, it is estimated that wind destroyed over a 100 million cubic metres of timber in a single storm in 1990; snow damage to European forests is estimated at 4 million cubic metres annually and fire accounts for the loss of around 5 hundred thousand hectares.

In response to this, a collaborative project between the Institute and other agencies in the UK, Finland, Sweden, Portugal and Ireland has developed, with EU support, a decision support tool for whole risk assess-ment of wind, snow, and fire at tree, stand and regional levels. The tool allows forest managers to assess and evaluate the risks of forest damage and to test the contribution of alternative management strategies to reducing risks.

A critical innovation in this project has been the bringing together of all the risk models within a single framework accessed by and structured within a World Wide Web (WWW) interface. This framework was developed by the MLURI group and was conceived from the outset as a means of not only enabling user access and model development but also as a way of allowing the different research groups to collaborate on the development and testing of the risk modelling systems in different bioclimatic and forestry contexts.

Underlying the framework there are several risk models that have been developed separately but grounded on common environmental and management issues. These include spatial and aspatial, mechanistic and empirical models. Integrating these models represents a considerable challenge and another novel aspect of the STORMS project has been the development of a standardised approach to the description of the data and the models (metadata and metamodel information). This has subsequently been adopted by DGXII as an exemplar for the development and operational use of metadata. The meta-information has been used to identify the key links that are required for users to assess the 'fitness for purpose' of a risk model relative to the data that are available to them. A user can therefore establish the value of the system to their own specific application.

The results of this project can be viewed on the WWW at: http://www.bamboo.mluri.sari.ac.uk/aair/aair-home.html and a CD-ROM is available as a teaching aid for graduate and postgraduate levels.

II) Assessing integrated land use options

Objectives

Our strategic objective concerns the analysis and synthesis of knowledge about the biophysical potential of land resources to support sustainable single/multiple land use systems, with the aim of creating land use decision support tools applicable at management unit and regional levels. Our short-term objectives are to develop (new initiatives are in italics):

- Understanding of low-input and integrated upland farming systems through field systems experiments (links with Land Use Options for Animals Programme, PU29).
- Simulation environment for modelling wildlife dynamics in hill grazing systems.
- *Farm-level environmental accounts for assessing sustainability (links with Socio-Economic and Policy Analysis Programme, PU22).*
- Decision-support system for assessing land use options at the management unit level (LADSS) (links to Development of Decision Support Systems Integrated Programme, IPU38).
- GIS-based land suitability analyses in relation to: organic waste recycling; land-based renewable energy (wind and biomass); wildlife habitats (links to Soil Quality, Contaminated Land & Waste Utilisation Programme, PU24 Land Use Options for Plants Programme, PU26 and Natural Heritage Management: Herbivore Foraging Programme, PU28 respectively).

The integrated land use research has been progressed through extensive collaboration with colleagues in France, Greece, Portugal, Italy and the Netherlands. This has recently been extended to include work with the Institute of Soil Science in Nanjing, (PR China) and also work in the Mid Zambezi Valley, with institutions in France and Portugal (linked to Natural Heritage Management: Herbivore Foraging Programme, PU28). The context of our work on development of DSS has been set through collaboration with colleagues in CSIRO in Australia and with AgResearch and Landcare in New Zealand. The leading edge nature of the work has been highlighted by a recent review of decision support systems for ecosystem management in the

USA (Mowrer, 1997) which concludes that: 'the ability to address social and economic issues lags far behind biophysical issues, and leaves the question of simultaneously addressing all three to future development. Many questions regarding appropriate mechanisms for aggregating and transforming data between scales remain unanswered, also. Consensus building remains a high priority in developing Ecosystem Management scenarios'.

Achievements

(Software developments in italics)

- Development of a GIS-based assessment procedure for evaluating alternative sites for biomass-to-energy plants. In collaboration with the Energy Technology Support Unit (Towers et *al.*, 1997 a & b).

- *Development and testing of a process-based model (ALWAYS) for simulating the interactions within an evolving agroforestry system. In collaboration with a consortium of UK and EU partners (Bergez and Msika, 1996; Bergez et al., in press, a & b)*

- *Prototype of an A-life based* (Swarm) *simulation modelling environment, called WEAVER, for studying the behaviour of grouse under differing management scenarios in collaboration with Aberdeen University and the Scottish Agricultural College.*

- *Completion of a prototype DSS for assessing land use options at the management unit level (LADSS) representing a unique coupling of GIS and expert-systems environments. In collaboration with Robert Gordon University, Smallworld and Gensym.*

Current Research

a) Assessing the potential for Short Rotation Coppice (SRC) in Scotland

This 2 year collaborative project with the Energy Technology Support Unit (ETSU) based at Harwell, supported by SOAEFD Flexible Funding, was aimed at identifying: a) the geographic potential for SRC in Scotland and b) developing a method to identify optimum locations for biomass-to-energy plants relative to the potential SRC resources, and the road and electricity transmission infrastructures.

The method used in assessing the potential for SRC was dependent upon a rule-based model for land evaluation based on soil, climate and topographic criteria. It was not possible to obtain detailed site/yield relationships so only general yield relationships were identified. The analysis showed that around 20,000 km^2 of Scotland is suited to the production of short rotation willow (Figure 3). The area suited to poplar is much less. Assuming a 5% take-up by farmers on this land it would yield sufficient feedstock to fuel between 20 and 25 5MW biomass-to-energy generating plants: this would be sufficient for some 25,000 domestic consumers.

In relation to optimal siting of biomass-to-energy generating plants, the study yielded some valuable insights. Currently the major site requirements relate to proximity to road and electricity grid infrastructures. However, our analysis, which used both these criteria and a further criterion based on the availability and security of feedstock supply, suggested that the latter criterion is potentially more important. Because running costs for biomass-to-energy plants, in particular feedstock transportation costs, are much higher than initial capital costs, it makes sense to select sites where haulage costs can be minimised.

By using a GIS, we analysed all the potential sites, defined on the basis of 33kV grid connections in Fife and Lanarkshire. By classifying the different types of road according to an average safe speed for a loaded lorry, we were able to define the accessibility of their agricultural hinterlands. Figure 4 provides an example for the 33kV substation at Newburgh in Fife. Since we already knew the potential of these areas to produce SRC from the suitability map, it was possible then to develop yield/travel time profiles for each of the potential sites. Figure 5 illustrates such profiles from two very different agricultural hinterlands: that around the Newburgh substation in Fife and that around the substation at Sorbie in Lanarkshire. From these profiles it can be clearly seen that the required 20,000 tonnes of dry feedstock could be easily obtained from the hinterland of the Newburgh substation. However, to

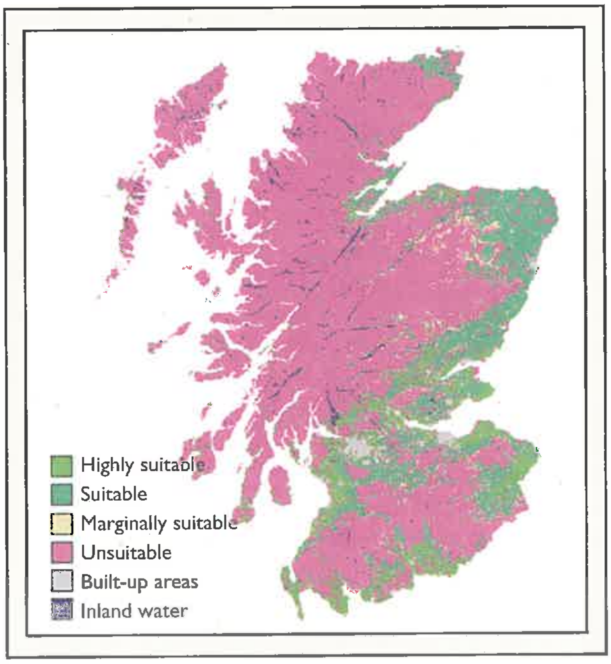


Figure 3. Land Suitability Assessment for Short Rotation Willow Production (Including an Assessment of Droughtiness and Exposure).

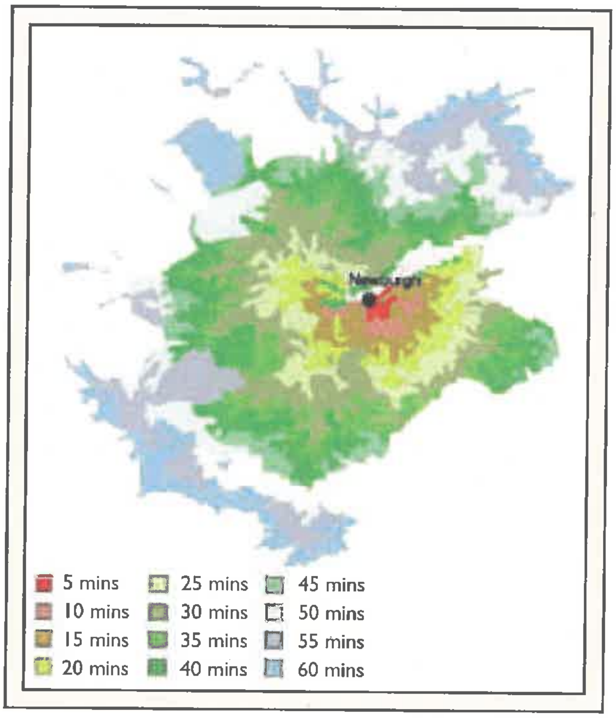


Figure 4. Travel time bands using road network in 5 minute intervals form Newburgh 33kV substation.

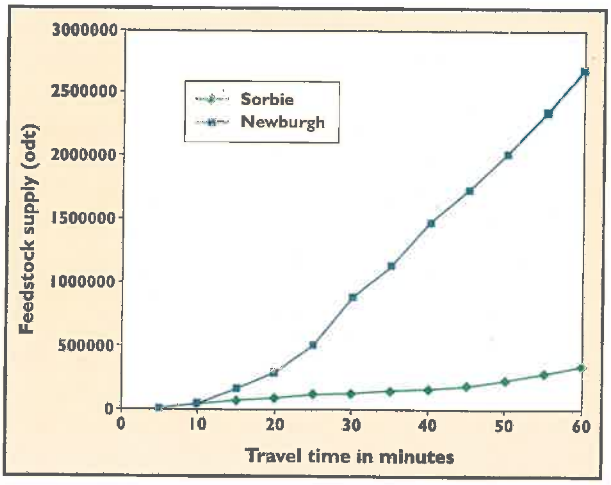


Figure 5. Feedstock supply (odts) in relation to travel time from two 33kV substations with contrasting catchment profiles.

secure the same amount from the hinterland of Sorbie would involve significantly higher transportation costs and would also be subject to a much higher risk where farmer uptake of SRC was low. Even within the comparatively favoured area of Fife our analyses show that there is a 100% difference between the most favoured and least favoured sites in terms of travel times required to produce the same feedstock.

This research represents a highly innovative approach to regional assessments of the potential for novel crops. It also illustrates the value of spatial decision support tools when evaluating alternative locations for processing plants. The results clearly illustrate the security (i.e. sustainability) of some sites as opposed to others. The study also shows that this type of locational analysis can reveal opportunities to provide targeted incentives for paying premia to specialised crop production in certain locations, since the premia can be traded off against reduced travel costs.

Our whole analysis depended upon assumptions about adoption/uptake rates. A further development of this work is to examine the factors that influence farmers' attitudes to SRC. This is the subject of a collaborative bid for EU funding under the THERMIE programme with ETSU, and other partners in France and Greece.

b) A Land Allocation Decision Support System (LADSS)

Our research programme mirrors the overall objective of the Institute to develop relevant land use decision support tools. Over the past 4 years our aim has been to create a tool appropriate to supporting strategic land use allocations at the management unit level. This would have value both to the land management and policy development communities.

The research has been primarily concerned with the development of a novel and interactive linkage between a object-oriented GIS environment developed by Smallworld Systems Ltd, and the G2 application development environment provided by the Gensym Corporation, and both of the companies have provided support to this research.

The prototype Land Allocation Decision Support System (LADSS) has been developed and tested within the context of an upland farm (i.e. livestock, grass, with limited arable, and forestry). LADSS is implemented as a series of knowledge bases principally relating to the land resources of the management unit and specific land use modules which cover suitability, productivity and financial returns relative to the bio-physical resources, management and grant regimes. Presently there are 2 livestock, 1 arable and 7 forestry options. The structure of the LADSS is outlined in Figure 6.

A critical aspect of the LADSS is that land use allocations may be made in several ways. These range from complete definition by the user, through a

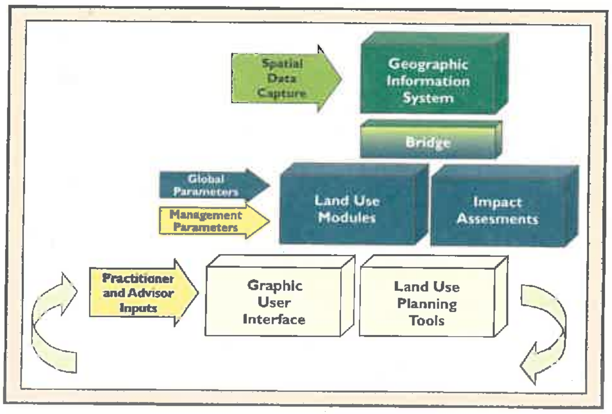


Figure 6. The components of the Land Allocation Decision Support System (LADSS). One of the critical innovations is the 'bridge' created between the Geographic Information System and the expert system components.

mixture of user-defined allocations with some system-defined ones, to the situation where all allocations are defined by the system. This spectrum reflects our desire to ensure that the users have the maximum opportunity to explore possible land use scenarios and their costs and benefits. In the prototype system these are currently evaluated only in financial terms. Net Present Value (NPV) is used to integrate the expected returns from annual enterprises with those from forestry. The interest rate and period over which the NPV is calculated can be defined by the user. Extending the valuation system to include conservation (e.g., biodiversity) indices and social (e.g., labour profiles) indices, is underway. A preliminary workshop has been held to gauge the reaction of potential users to the prototype and to identify their principal needs and priorities. Future developments will be achieved through active participation of a users'group.

LADSS represents the initial outcome of our work to develop user-oriented tools for exploring integrated land use options. It is unique in a world context, both in terms of the technical solution that has been developed, and in terms of its capacity for user involvement. It has also highlighted significant scientific issues: in particular those relating to rapid resource characterisation; rescaling of farm enterprise models and their integration; and the need to develop a wider range of objective measures for valuing non-economic outputs from farming systems (e.g., conservation, amenity, environment etc.). Some of the latter issues are being addressed in our work on farm-level environmental accounting.

iii) Prediction of land use change

Objectives

In this new area of work our objective relates to research and development of systems theory and simulation modelling tools for exploring potential patterns of land use change at farm and regional levels, under different economic and policy circumstances.

Short-term research objectives are to develop (new initiatives are in italics):

- *Indicators of risk and resilience in relation to sustainability of UK farming sectors.*
- *A simulation modelling Framework for the Evaluation and Assessment of Regional Land Use Scenarios (FEARLUS)*

This work is strongly related to the considerable efforts underway in modelling complex systems throughout the world. This came together in 1984 with the founding of the Santa Fe Institute (Waldrop, 1992). The Sante Fe Institute's (SFI) research covers many topics of interest to the Institute and Land Use Science Group staff have visited the SFI on a number of occasions.

A major theme of the SFI's research has been in the modelling of economies and societies using the novel approaches of complex systems science. In 1993, the SFI along with the World Resources Institute and the Brookings Institution launched a collaborative research project to explore the question 'how can we achieve a sustainable existence on this planet by the middle of the next century?'. This project has resulted in a considerable effort in modelling the development of societies (Wright, 1997). The outcome of the research is a modelling system that has considerable potential for modelling societies and social change (Epstein, 1997).

It is some distance from these models to a model of land use change in Scotland, but current efforts at the Institute are investigating novel approaches to using knowledge in complex system simulations (Hare *et al.*, submitted). The extension of our approach to the complex system that includes the social and economic aspects of land use change is the core effort of the FEARLUS project.

Relevance to End Users and Future Developments

The approach adopted within this programme is user-oriented and participatory. To some extent, therefore, the precise direction of our research is dependent upon the outcome of user interactions and feedback. For example, we are actively involving land managers in the development of the LADSS and, as a result of initial user feedback, have prioritised new functionality. A further example is the involvement of a 'customer focus group' (Wright and Morgan-Davis, 1997) to guide our development of flood risk modelling within a major EU remote sensing demonstration project called HYDALP (Wright *et al.* 1998). A similar approach has been adopted with the development of the WEAVER product and will be used for the FEARLUS project. This work represents a major step towards the creation of multi-scale modelling environment and builds on the considerable achievements within SYMOLAC, LADSS and WEAVER, in terms of the use of advanced AI and complex systems techniques.

The major applications initiative will continue to move towards tackling the issues of sustainability, particularly in terms of assessing the social, economic, and environmental dimensions of rural development and change. This will require increasingly close links with the socio-economic perspectives within the Sustainable Integrated Land Use Options theme.

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There is an underlying trade-off implicit in sustainable development between economic activity and the protection of such assets as biodiversity, landscape, water resources and the ability of the environment to assimilate wastes.

Socio-Economic and Policy Analysis

Economics research plays a major role in the process of making human activities more sustainable: decisions on our use of the environment can have important implications for economic activity and the choices involved are rarely simple. There is an underlying trade-off implicit in sustainable development between economic activity and the protection of such assets as biodiversity, landscape, water resources, and the ability of the environment to assimilate wastes. Since the United Nations Conference on Environment and Development in 1992, governments have sought to interpret the concept to sustainable development and transfer it into policy. This has raised issues of how sustainability might be measured, how environmental resources might be better managed at scales that range from regional to global, and how we might move to a more sustainable trajectory in economic growth. A series of action plans for environmental management at UK and European levels are being developed for such areas as biodiversity, water basin management and transport, and the EU Commission is contributing through its 5th Environmental Action Plan. Much of the economics research at MLURI is aimed at supporting the development of effective policy measures for improving the management of the environment and, where appropriate, the activities of businesses and sectors that make demands on environmental capacity.

Within the Institute the programme of economics research contributes to the theme of Sustainable Integrated Land Use Options. A substantial part of its research involves collaborative work with other Institute programmes – in particular those concerned with Atmospheric Deposition, Land Use and Water Quality Management (PU23), Natural Heritage Management - Herbivore Foraging (PU28) and Land Use Options for Animals (PU29). It contributes to the Integrated Programme Unit, Long-term Measurement and Monitoring of Change (IPU37) through a study of the economics of environmental monitoring.

Strategic Objectives

The programme concentrates on a number of topics, each of which contributes a distinctive element to the analysis and implementation of sustainability.

- **Developing methods for measuring sustainability.** These include the construction of sustainability accounts, the use of indicators of sustainable activity, and through improved economic valuation of the environment. Our specific concern is with managing rural resources. This research complements national development of environmental accounts and environmental indicators (DoE, 1996).

- **Developing valuations for ecosystems and landscapes.** This is central to the subject area of environmental economics and it allows more informed debate about environmental choices. Our research is focused on the economic valuation of the benefits from policies that enhance the environment, such as those that protect ecosystems and enhance landscape and water resources. Within this, a particular concern is to develop methods that will assist in valuing attributes of the environment such as landscape features or specific species and habitats.

- **Improving policy design: modelling the environmental behaviour of farmers and landowners.** There is widespread interest in making greater use of economic instruments to deliver environmental policies and sectoral policies that impact on the environment (e.g. DETR, 1997). Researching options for contract design between agencies and operators is essential for effective management of the environment.

- **Natural resource management: – integrating environmental priorities with policy mechanisms.** This theme investigates different approaches for specifying policy objectives for the protection and investment in natural capital assets. It concentrates both on valuation systems, incorporating both pubic and expert preferences, and the policy making process that seeks to create workable and effective policies. The focus has been on policies for ecosystem regeneration.

Current Research

Developing methods for measuring sustainability

This research takes as its starting point Solow's (1993) theory of sustainable resource management as generalised by Pearce *et al.* (1994). In this the objective is to maintain the total stock of manufactured, human and natural capital, and to apply conditions that protect 'critical' natural resources. Whilst this has been applied at the national level to mainly non-renewable resources there are major problems of measurement, valuation and substitution within economies that have made it more difficult to implement at the sectoral or regional level. We have explored alternative approaches and drawn on accounting (Whitby & Adger, 1996; Vaze & Balchin, 1996) and bio-physical indicator methods (Stanners & Bourdeau, 1995) in the context of more specific environmental functions – assimilative capacities and ecosystem services (Constanza *et al.*, 1997).

One approach to sustainable resource management is through the use of environmental and sustainability indicators that alert stakeholders to unsustainable activities. Our research has taken the OECD (1994) pressure-state-response framework and modified it for use at a regional scale (Crabtree & Bayfield, in press). This built on research for the Cairngorms Partnership (an agency with the role of sustainable management of the Cairngorms mountain area) in which sets of indicators were established to measure environmental and socio-economic change. An EU DGVI workshop on agri-environmental indicators has brought together the theoretical and practical issues. Whilst this approach is central to government management of the environment (DoE, 1996) we have highlighted the need for more attention to be given to indicators of the biophysical processes and to the use of indicators for setting targets for environmental action (Figure 1).

We are exploring the idea of incorporating sustainability impacts within the accounting procedures of individual firms, and specifically farm firms, since these have a major role in maintaining biodiversity and landscape resources. Farms may also pollute soil, water and air through mineral and gaseous emissions. Since most effects are off-farm, accounting models for emission of nitrates, greenhouse gases and impacts on biodiversity and landscape are being developed to measure the environmental performance of individual farms. This methodology is currently being tested but it has raised doubts about the extent to which conclusions on sustainable management can be made at the business or local level unless there is a clear policy framework in which impacts can be evaluated and priced. Our research will link business to the appropriate scales for policy intervention.

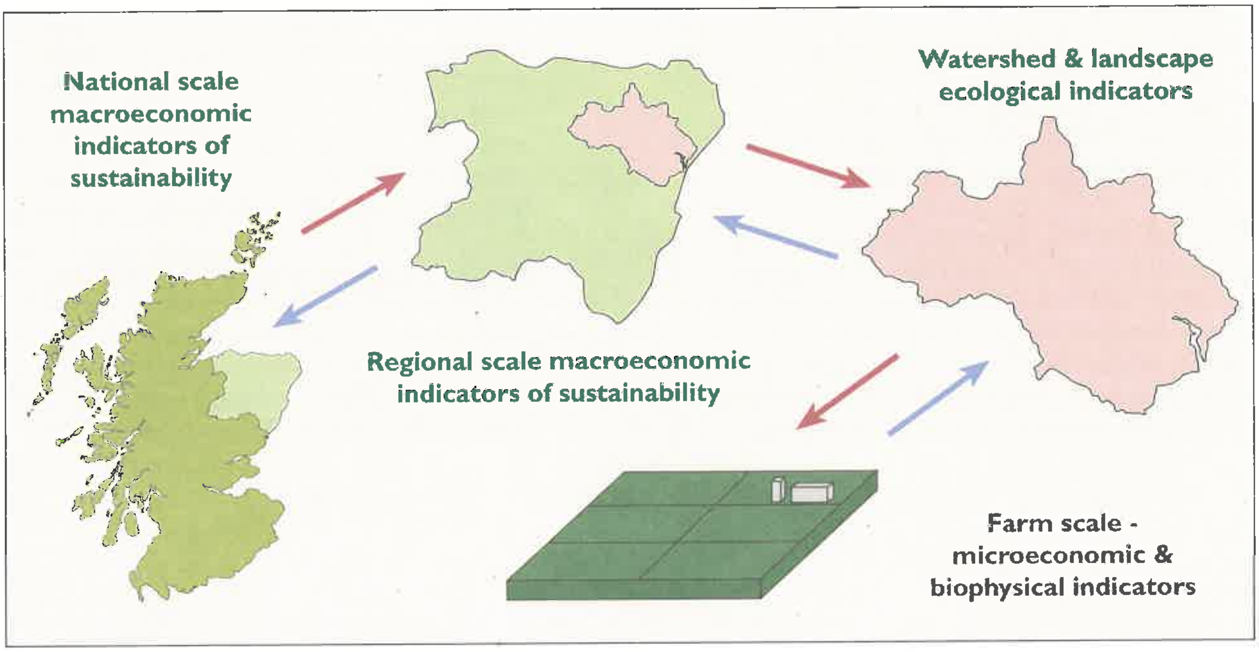

Figure 1. The hierarchical nature of agricultural sytems (after Lowrance et al., 1986).

Developing valuations for ecosystems and landscapes

Pricing the environment allows environmental decisions to be incorporated more fully in the utilitarian basis of welfare economics (Krutilla, 1967). Not surprisingly therefore, considerable research has been directed at economic valuation of the environment. We have concentrated on the use of contingent valuation (CV) and choice experiments in order to underpin policy decisions on land use with a workable methodology. CV has long been contentious because of difficulty in validating results (Hanemann, 1994; Navrud and Veisten, 1996). An opportunity arose to test CV results when a charitable fund was set up for community purchase of the island of Eigg. Comparisons between real and hypothetical payments were made in a large public mail survey. Real payments exceeded hypothetical (CV) payments although the differences were not significant. Despite the specific context of charitable giving the results do suggest that CV methods can reliably measure preferences (Table 1).

Campaign Real	
Mean Donation (£)	3.71
Number of respondents	182
95% Confidence Limits	£1.59 - £6.33
Campaign Hypothetical	
Mean Donation (£)	3.41
Number of respondents	188
95% Confidence Limits	£2.05 - £5.19

Table 1. Comparison of real & hypotheical charitable donations.

We have been concerned to develop beyond conventional CV methods to those that produce a valuation of specific elements of the environment. This is important if specific environmental features are to be valued – an important requirement for the development of effective countryside policies. One approach with potential to achieve this is choice experiments, in which members of the public are questioned about their preferences for different combinations of environmental elements. We applied this to Environmentally Sensitive Area (ESA) Policy (Hanley *et al.*, 1998) and now in a quite different context – the impacts of changing upland landscapes on demand for deer stalking (Bullock *et al.*, in press). The results have been promising and we intend to continue with development of this method which has considerable potential for assisting policy design. It does, however, require more efficient experimental designs and simpler methods of analysis if the costs of implementation are to be reduced to a level consistent with its practical use.

Improving policy design: modelling the environmental behaviour of farmers and landowners.

The use of regulation and incentive mechanisms by government to control and direct the private provision of public services has spawned extensive literature on the economics of regulation and principal-agent models (e.g. Campbell, 1995). EU policies already provide for a range of incentive payment to farmers and this element is likely to expand as landowners are rewarded for their provision of environmental goods. We have concentrated on modelling policy uptake in order to work towards more sophisticated design of incentives. To date this has concentrated on contract mechanisms linking government and farmer 'agents' using contextual, statistical modelling (Crabtree *et al.*, 1998). We have defined the key characteristics of farms and farmers that predispose entry into incentive-driven schemes for tree planting (Figure 2). This explains the current spatial distribution of tree planting and raises questions about whether policy is delivering according to its objectives.

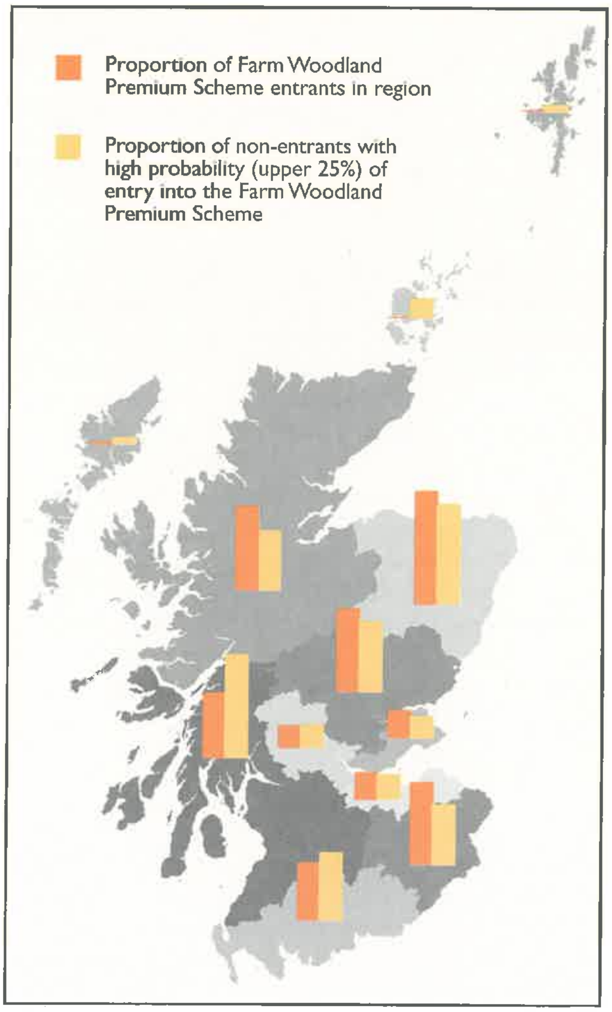

Figure 2. The regional distribution of entrant and non-entrant holdings on the basis of predicted probability of entry.

A second environmental service that farmers can provide is the provision of access. It is an example of the possible broadening of activities of farmers in which environmental goods are produced and paid for from public expenditure. However, publicly funded access schemes have had limited success and this has raised the issue of whether incentive design could be improved. We have used likely distributions for the access supply response on the part of farmers and the willingness-to-pay (WTP) of users in order to explore design alternatives. The degree of skewness in WTP and the costs of site selection and administration are crucial determinants of policy success. We conclude, nevertheless, that there is no guarantee that any efficient public purchase of access provision is feasible because of the high transaction costs involved in relation to WTP.

Natural resource management: – integrating environmental priorities with policy mechanisms

Sustainable resource management consists not only of resource protection but also of investment in new natural capital. The UK Biodiversity Action Plan identifies priorities for habitat and species but this leaves the economic problem of how to determine the magnitude of benefits and how to deliver policy through agreements with landowners and other agents. There are important general issues concerning the role of public versus expert preferences and the preferences of different societal groups who may also act as interest groups. Our interest is in developing alternative bases for policy analysis other than the aggregate welfare model.

We have taken native pinewood restoration as an example of this type of issue. Both public valuation of restoration policies using CV and expert criteria for the restoration process were undertaken (Macmillan *et al.*, in press). The public WTP supported pinewood restoration policies but the expert panel were more specific in their preferences, scoring natural regeneration higher than new planting on the basis of higher ecological benefits. By modelling the link between the incentive structure and the net benefits from different forest designs it has been possible to evaluate existing policy delivery. This line of research will be developed since it has the ability to link utilitarian policy models to those based on public choice and the policy-making process.

Achievements

- Undertook economic valuation of benefits from ESA Policy (with University of Stirling) (Hanley *et al.*, 1998). This demonstrated benefits from ESA policy that greatly exceeded the financial costs, with the principal benefit in terms of non-use benefits rather than those accruing to tourists or local residents in the ESA areas.

- Developed a generic approach to measuring sustainability at local scale (Crabtree & Bayfield, in press). This identified the issues in measuring sustainability at sub-global scale and indicated when and under what conditions more local sustain-ability measures are possible. It relates to the Agenda 21 concern with local contributions to the sustainability debate and the specification of local action plans.

- Developed strategy for native pinewood ecosystem restoration combining benefit valuation with incentive scheme structure (Macmillan *et al.*, in press). This analysis indicated that the present grant aid structure gave insufficient weight to ecosystem expansion through natural regeneration

- Developed choice experimental approaches to the economic valuation of environmental attributes (e.g. specific elements of landscape or biodiversity). This uses statistically designed experiments to explore the preferences of respondents and so provides a utility-based ranking of policy benefits.

- Contributed to an appraisal of EU policy impacts on the environment in the mountain areas of Europe. This demonstrated complex impacts of changing land management on mountain environments with abandonment, intensification and transfers from agriculture to other use (e.g. forestry) commonly occurring (Crabtree & MacDonald, 1998).

Future Developments

Although economic analysis in the past has largely been non-spatial we have identified potentially major benefits from placing the economic analysis of land use issues in a spatial framework. The European spatial development perspective has outlined important spatial issues for the natural heritage and for rural areas. We intend to explore better integration of spatial analysis with economic models in order to provide better analytical tools for policy concerning rural sustainability and environmental management

Since the interaction between economic activity and the environment is fundamental to sustainability we intend to devote more resources to modelling the interlinkages between economic activity and environmental impacts. This will use both partial and general equilibrium models and will be aimed at identifying how activities associated with a range of policies (including structural and environmental policies) contribute or detract from sustainable development. These models will also be used to investigate rural-urban relationships and their relevance to rural sustainability.

Finally we intend to develop methods for valuing environmental features such as biodiversity, habitats and specific elements in the landscape such that agri-environmental policies can be fine-tuned to provide services that match up with public preferences. It will be combined with research on expert and interest group formulations of priorities so as to identify how different concepts of policy making may result in different policy designs.

Relevance to End Users

Most of the economics research is directly relevant to the design and evaluation of government policies for land use and the environment. We have undertaken the economic evaluation of ESA policy and are currently contracted to Scottish Office for research on the income benefits from ESAs to farmers and local economies. We have undertaken research for the Scottish Natural Heritage (SNH) on habitat restoration and collaborated with Royal Society for the Protection of Birds (RSPB) in work on cost-effectiveness analysis for environmental policies. Two important studies on the economic aspects of water pollution have been undertaken for Scottish Office and SNH.

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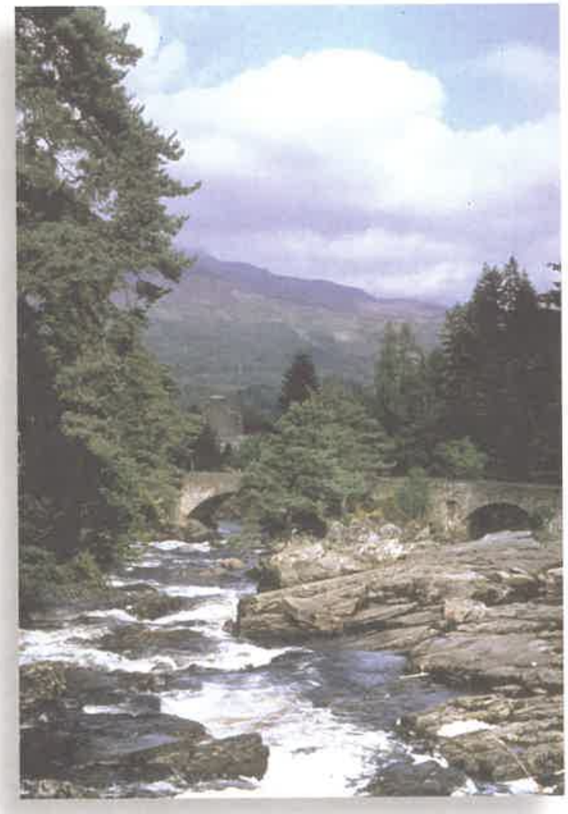

Our research is concerned with the hydrological and hydrochemical interactions of pollutants within catchment systems and the development of decision support systems for resource managers and policy makers.

Atmospheric Deposition, Land Use and Water Quality Management

The water resource is indispensable for nearly all human activities, and for sustaining the ecosystems on which our and future generations depend.

Previously, the principal objectives of water development policy were focused around economic development, be it the provision of supplies for urban development, the generation of power, or for the production of foodstuffs and consumables.

However, as a consequence of increasing pressures on water resources and the recognised variability of the hydrological cycle a new debate has begun. This is reflected in the nature of the statements coming from the Mar del Plata water conference from the Earth Summit in Rio de Janeiro, policy papers from the World Bank, the Global Water partnership, and others. These efforts call for new definitions and concepts in an effort to incorporate characteristics of sustainability and equity into water resource planning. Developing sustainability goals has become a major policy priority, and requires placing a high value on maintaining the integrity of water resources and the flora, fauna and human societies that have developed around them. Rather than continuously trying to find the water to meet some projection of future desires, it is time to plan for meeting present and future human and ecological needs within the limits of our resources (Lundquist and Gleick, 1997).

Another key element is the realisation that water planning and land use planning should no longer be undertaken in isolation. The interaction between water, land and ecosystem management necessitate closer co-ordination which has highlighted the watershed or catchment as the appropriate spatial unit for Institutional management and planning. For planning purposes a catchment is defined as a discrete geographical area with boundaries derived primarily from the topographical surface water catchment, but taking into account groundwater boundaries where they are significantly different.

The European Community made the management of water resources one of its earliest priorities and has made great strides in reducing industrial pollution from both industry and waste water treatment. The proposed Water Framework Directive (COM(97)49) builds on this, and is intended to repeal a number of older pieces of legislation. It seeks to integrate the management of freshwater resources and supplies with the protection of its quality. In response to Agenda 21, it is committed to achieve this goal through an integrated approach which combines legislative quality standards and emissions limits within coherent water management systems based not on administrative boundaries but on natural river basins. Member States are obliged to put into operation measures which are regarded as necessary to achieve 'good' status for all waters by 2007 in the form of River Basin Management Plans, which will be revised every six years. The analysis of the characteristics of River Basin Districts based on geographical, geological, hydrographical, demographic, land use and economic criteria is intended to be completed by the end of 2001.

Strategic Objectives

These criteria form the basis of the strategic research conducted by the Institute on the science theme of 'Integrated Catchment Management'. The research determines the hydrological and hydrochemical interactions of pollutants within catchment systems, and in particular those aspects that enhance the pressures on the water and land resource from acidification and eutrophication (Figure 1). A fundamental element of this is the elucidation of land use management factors at a number of spatial scales, and the downstream consequences and interactions of pollutants. The development of spatial decision support systems is seen as a key priority of the programme, and aims to bridge the gap between process based understanding and the requirements of resource managers and policy makers.

Figure 1. Eutrophication of standing waters.

One key element of the proposed Water Framework Directive is that the Commission is fully committed to the principle that *all* proposals contained within the Directive should be accompanied by economic analysis, which include not only the cost of providing the necessary services for water uses, but also the environmental and resource depletion costs. These latter concerns might be relevant depending on the hydrological and socio-economic conditions as well as the legal and administrative provisions within the river basin. Associated socio-economic costs represent the costs of environmental damage that certain water users impose on other users, including future users, or on society as a whole and the costs of foregone opportunities which other water users suffer due to depletion of a resource beyond its natural rate of recharge or recovery. The Atmospheric Deposition, Land Use and Water Quality Management Programme (PU23) links closely with research being undertaken within the Socio-Economic and Policy Analysis Programme (PU22) in order to address these issues, and places the Institute in a strategic position to respond to the requirements of the Directive and its objectives. Indeed, the principles of multi-disciplinary integration are already a feature of the current research portfolio.

For example, the development of a catchment management plan for the River Ythan in NE Scotland has focused on the elucidation of the nature of the problem and how historical land management practices may have driven this change (Domburg *et al.*, in press). The future objective of policy would be to optimise land use and management, whilst aiming to minimise the impact on farming practices and incomes. Similarly, work on the spatio-temporal modelling of opportunities and constraints associated with organic waste recycling to land in response to the current EU Urban Waste Waters Treatment Directive being conducted within Soil Quality, Contaminated Land and Waste Utilisation Programme (PU24), has identified areas within catchment basins which are the preferred areas for organic waste utilisation.

The development and assessment of a numerical technique for elucidating the complex signals contained in flow and quality records has been developed in liaison with the Integrated Programme Unit on Long-term Measurement and Monitoring of Change (IPU37), and has enhanced our understanding of process response contained in environmental data records collected from a number of different monitoring sites throughout Scotland. Similarly, the integration of monitoring data with the predictive potential of spatial land use modelling has resulted in the development of a prototype Spatial Decision Support System (DSS) for Lochs in the Scottish Standing Waters Classification Scheme (with the Integrated Programme Unit, Development of Decision Support Systems, IPU38), which aims to provide a proactive tool for the integration of land and water quality management.

Description of the Programme

Within the overall research strategy, specific efforts have been directed towards elucidating the impact of both extensive and intensive land management practices on water quality at different spatial scales within catchment systems. In the uplands, research has primarily been focused on the interaction of commercial afforestation and the deposition of sulphur and nitrogen compounds from the atmosphere. Responses have been determined through a combination of field, laboratory, and modelling approaches, and interpreted using the concept of critical loads. Recent research has concentrated on an evaluation of the mechanisms controlling the calculation of critical loads, in particular the role of mineral weathering processes and their integration into currently utilised models. In the intensive lowlands, research is primarily directed to understanding the mechanisms through which nutrients such as nitrogen and phosphorus are mobilised under different land management systems and to quantify their contribution to stream water and sediment quality. This work has been set historically in the context of European environmental and water quality control legislation, which is now subsumed within the proposed Water Framework Directive.

As regulatory authorities have become more successful at tackling the problem of point source pollution, diffuse sources have become relatively more important. It is interesting to note that in the draft

Water Framework Directive, there is a realisation that there is not one simple solution to the question of diffuse pollution, indeed 'the range of solutions is as wide as the range of problems'. However, the Directive does include provisions for enhancing the co-ordination of efforts, and identifying and addressing problems at Regional, National, and European scales. It is perceived that the most appropriate mechanism is that through participatory approaches, involving all of the appropriate stakeholders, and through education based on relevant scientific research. The recent research programme on the River Ythan specifically involved the integration of a multi-disciplinary approach involving the farming community at all stages, and the final scientific outcomes of the work were presented at an information exchange seminar during 1998.

Integrated Catchment Management - Specific Objectives

1. Extensively managed upland systems

- Identify sources and sinks of major ion fluxes in natural and semi-natural systems.
- Measure the impacts of atmospheric deposition of S and N on ecosystem function.
- Assess critical loads of acidity, and describe the role of mineral weathering processes.
- Evaluate impacts of commercial forest management on water quality.
- Determine the efficacy of terrestrial liming on acidified catchments.
- Measure losses of total N and P, and the interaction of in-stream processes.

2. Intensively managed lowland systems

- Identify sources and sinks of major ion fluxes within highly managed systems.
- Quantify hydrochemical consequences of intensive animal farming practices.
- Identify the contribution and pathways of soil derived particles to the suspended loads of rivers.
- Develop algal bio-monitors for the assessment of trophic interactions.
- Identify spatial quality of groundwater resources in arable lowland catchments.

3. Basin Scaling

- Identify key hydrological and hydrochemical processes at the catchment scale.
- Develop procedures for using point measurements to represent field scale processes.
- Assess the impact of anthropogenic activities on water quality and quantity.
- Develop distributed catchment hydrological and hydrochemical models.
- Identify the significance of physical heterogeneity, and soil physical characteristics in catchment scaling.
- Extrapolate the application of catchment models to regional, National, and European scales.

The Catchment Management programme is underpinned by a broad science base on the topic of 'Transport and Scaling', which includes research on solution/particulate transport mechanisms, groundwater/surface water interactions, geochemical controls, hillslope hydrology and catchment scaling methodologies.

Achievements

- Development of a prototype spatial decision support system for the management and classification of standing waters in Scotland.
- Assessment of continued acidification and rates of recovery in selected Scottish sensitive catchments under proposed European emission control strategies.
- Development and application of an algal bioassay to assess the impact of nutrient enrichment on eutrophication responses.
- Development and assessment of a numerical technique for elucidating the complex signals contained in flow and water quality records.
- Retention of atmospheric nitrogen inputs by moss vegetation vary between sites depending on the water table depth, phosphorus content, and nitrogen concentration of the plant tissues.
- *Sphagnum* mosses receiving inorganic nitrogen release DON most probably as amino acids. Accumulations of DON in peats suggest that the fate of this N is unclear.
- Nitrogen and phosphorus interactions in peaty soils are important for the fate of N and also the potential depletion of phosphorus from the surface horizons.
- Development of a framework to enable the calculation of input-output balances for nitrogen and phosphorus at the farm scale.
- Ranking of land area with respect to the size of nitrogen and phosphorus surpluses at the regional scale.
- Evaluation of weathering rate calculations used in critical load assessments.

Current Research

Assessment of critical load sensitivity

In March this year the European Commission put forward a new Community strategy to combat acidification. This stems from the realisation that although Europe has substantially reduced emissions of SO_2 from power plants, critical loads in many regions will continue to be exceeded which will result in damage to the biodiversity of terrestrial and aquatic ecosystems, such that sustainable recovery will not take place until the critical load for that ecosystem is not exceeded. The EU have recognised that the target for meeting the ultimate objective of no exceedance of critical loads was going to be difficult to meet, and an interim target has been identified. This so called 'gap-closure' strategy proposed that there should be a reduction in the total area of sensitive ecosystems in which critical loads were exceeded in 1990 by at least 50% by the year 2010. Fundamental to achieving such targets is a need to characterise the inherent uncertainty in the determination of critical loads, both in terms of the methodology and ecosystem sensitivity based on dose response criteria.

In this respect substantial progress has been made in the determination of critical loads, specifically the research has evaluated the different methods for calculating weathering rates, a core component of the critical loads approach. The principal findings suggest that current methods of weathering rate determination and prediction contain large uncertainties. The propagation of those uncertainties is largely associated with those attributes of soils and ecosystems that are most difficult to assess and monitor (Hodson *et al.*, 1996; Hodson *et al.*, 1997). One future element of this work is how best to portray this uncertainty to the end-user policy makers involved in the development of emission abatement strategies.

The fate of atmospheric N inputs to areas of semi-natural vegetation

International collaborative studies on the fate of NH_4NO_3 to raised bogs has shown that the retention of N by *Sphagnum* moss and by peat is extremely variable between sites. The role of phosphorus deficiency which is characteristic of many of these upland peaty soils is to limit N retention and increase the contents of ammonium nitrogen at lower depths in the peat (Williams *et al.*, submitted, a). Water table depth influences the nitrogen content of the surface vegetation and it has been postulated from the results of this work that the incorporation of additional nitrogen is also dependent on the nitrogen status of the plant, i.e. the potential for N retention decreases as N concentration increases. This implies limits on the capacity of sites to retain inorganic N and saturation levels beyond which N moves into the peat profile and seepage waters.

Concentrations of dissolved organic nitrogen (DON) in peaty soils exceed those of inorganic forms and this is also the case in upland stream waters (Edwards *et al.*, 1996). Experimentally applied inputs of N, equivalent to 100 kg N ha^{-1} yr^{-1}, stimulated the release of DON from *Sphagnum* mosses *in situ* (Williams and Silcock, 1997). This has been confirmed at lower levels of N inputs (30 kg N ha^{-1} yr^{-1}) using ^{15}N labelled NH_4NO_3. At present there is no basis for comparing the characteristics of DON in soils and waters across a range of different soil and vegetation types. The importance of this DON for water quality and its forms and origins are the subject of the future research programme.

Averaged across five mire sites, the addition of NH_4NO_3 decreased the total phosphorus content of the surface horizons and this effect was greater at sites which contained the most phosphorus. Experiments on the effects of phosphorus additions on nitrogen pools showed that P increased the retention of $^{15}NH_4$ and $^{15}NO_3$ in *Sphagnum* moss (Williams *et al.*, submitted, b). Greater utilisation of N in the presence of P was reflected in lower contents of NH_4-N and DON where P had been applied.

The impact of land management practices on hydrochemical responses

Nitrate-N (NO_3-N) and phosphate (PO_4-P) in catchment inputs and outputs have been compared and contrasted in six streams draining small agricultural catchments in the west and north-east of Scotland (Hooda *et al.*, 1997a & 1997b). Forms of intensive animal farming ranging between beef and dairy cattle, sheep and poultry give different sources for potential NO_3-N and PO_4-P leakage from the systems. While streams bordered by intensive cereal production give rise to the largest inputs to surface waters, climatic influences result in the more efficient use of fertiliser- and farm waste-N in the west, and an enhanced potential for N-loss to waters in the cooler north-east, regardless of the N-inputs being considerably smaller in the latter region. Although the EC Nitrate Directive limit of 11.3 mg NO_3-N l^{-1} was not exceeded, peak values occurring during summer baseflows and autumn soil rewetting were commonly larger than the 'target' maximum concentration of 5.65 mg l^{-1}. The loss of P from soils to streamwaters was greater from catchments with intensive dairy cattle farming in the west than the less intensively stocked/arable catchments in the north-east, with striking differences being seen between the two regions. In the north-east, intensive animal farming resulted in less P loss in drainage water than arable management. Larger mean annual concentrations are seen in the west (0.076 - 0.142 mg PO_4-P l^{-1} as molybdate-reactive phosphate - MRP) compared with the north-east (0.012 - 0.025 mg PO_4-P l^{-1}), a feature caused by the combination of limited P-retention in the western gleysols and smaller inputs to the largely-podzolic north-eastern catchments.

Stream concentrations are decreased by dilution during winter stormflows and increase during summer baseflow and at the beginning of autumn soil rewetting. Although these losses are not totally unexpected in intensive agricultural areas, increasing atmospheric deposition of nitrogen has been cited as the major cause of N-saturation in upland areas which, in the past, have been N-limited. Extensive farming methods can create mosaics of improved land within indigenous moorland vegetation and the combination of atmospheric deposition and agricultural inputs can lead to an apparent release of NO_3-N within the system.

This can be compounded by land improvement features such as liming, which gives rise to a mobilisation of soluble and colloidal organic matter into soil drainage waters (Anderson *et al.,* 1997), and the combination with inorganic- and organic-N can give rise to potential groundwater eutrophication. Phosphate also has increased potential for leaching under such conditions, especially in soils which contain easily-mobilised Fe sources, which lead to enhanced P complexation by dissolved organic matter, facilitating catchment fluxes of total phosphorus. Features such as these are currently under study within the Integrated Catchment Management programme, at Glensaugh Experimental Station. Although there is good evidence to suggest that increasing proportions of crop land correlate well with nutrient discharges to surface waters, in less-intensively managed land, water pathways over and through soils have a greater influence on discharges. Current hypotheses are based on the derivation of baseflow chemistries and their influence on catchment outputs; nitrate-N is readily leached into groundwater and thus appears as a different end-member of any mixing model, with organic C & N derived mainly from surface or shallow sub-surface flow. This hypothesis is currently under test using Glensaugh Research Station soil drainage and surface water databases.

Downstream consequences of pollutants - eutrophication

Rivers, by their nature, pose a special range of problems for the assessment of eutrophication: in particular, the background concentrations of nitrogen and phosphorus can vary over an order of magnitude within a single river system. As a consequence algal growth responses to individual pollution inputs will have a high degree of spatial/temporal dependence. Appreciation of this situation raises questions about the usefulness of legislative guidelines which are based on single concentration values, or poorly defined terms such as "eutrophication" in their assessment of water quality (COM 91/271/EEC (1991), US Toxic Substances Control Act (1985)). A new approach is required which has led to the development at the Institute, in collaboration with the University of Dundee, of a novel *in situ* biomonitor using alginate immobiled algae, which are entrapped onto a nylon mesh. The immobilsed film (which is robust and easily handled) is incubated in aquatic systems, and subsequently recovered after a prescribed time for rapid measurement of responses using a simple automated method of absorbance determination corresponding to chlorophyll-*a* concentration, which in turn can be used as a measure of algal growth response (Figure 2). A major advantage of this system is that native strains of algal species (isolated directly from the water source under investigation) can be incorporated directly into the biomonitor. This ensures that any pre-adaptation to prevailing local conditions by the algal community is incorporated within the bioassay itself. This is particularly useful for the prediction of growth responses of potentially hazardous algae, for example, toxic cyanobacteria. The technique provides a novel site-specific environmentally realistic estimate of the eutrophying potential of water bodies, through a direct cause - effect response, which would potentially eliminate the uncertainty associated with water quality assessment and classification using traditional approaches (Twist *et al.,* 1997, Twist *et al.,* in press) (Figure 3).

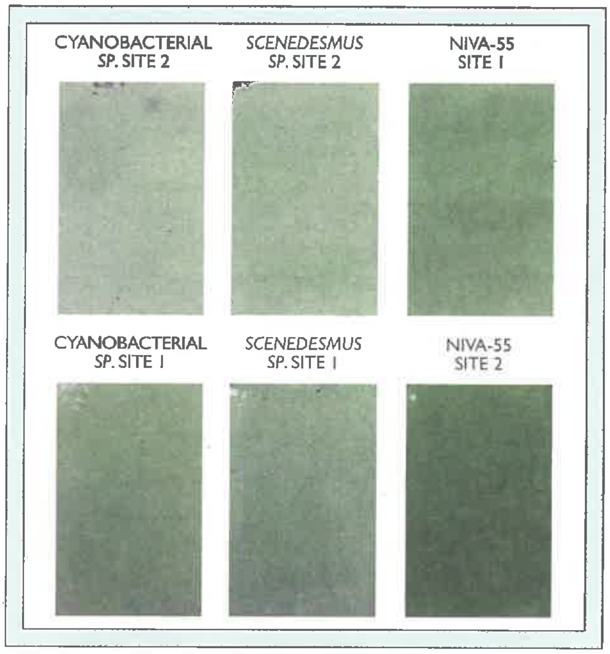

Figure 2. Algal biomonitor responses.

Figure 3. Stream incubation of algal biomonitors.

Downstream consequences of pollutants - sediment interactions

Selective erosion of fine particle sized soil material has two influences regarding the P chemistry of surface waters. This relates to the common inverse relationship between particle size and P content (enrichment ratio) which results in enhanced P loss (Maguire *et al.*, in press; House *et al.*, in press). This is counteracted by the greater sorption properties of finer material which results in the maintenance of relatively small equilibrium solution P concentrations (EPc). The sensitivity of EPc to factors such as solid to solution ratio, electrolyte concentration, mineralogy, and previous land management practices have been assessed and suspended sediment collected from six east coast rivers. The river catchments were selected on the basis of dominant land uses, soil types, and industrial/domestic point sources in order to extrapolate our understanding of P solution/solid phase dynamics into the field situation (Ernstberger, 1997).

Role of environmental monitoring schemes

The role of environmental monitoring and data networking is essential to achieving the objective of assessing the impacts of global change on natural and managed systems and their sustainability. Scientific criteria for good environmental management are highly influenced by the quality of both historical and present day data collection. Historically, the lack of data was either attributable to lack of data collection or lack of data sharing. Multi-disciplinary approaches require the blending and reinforcing of conventional information systems with modern technology and equipment, as well as the collection of pertinent information.

Recently the Scottish Office Agriculture, Environment and Fisheries Department commissioned a review of the Harmonised Monitoring Scheme in Scotland. This long-term database which was initiated in 1975 had the original objectives of deriving mass load estimates for various water quality parameters in order to fulfil the UK's international obligations to bodies such as the Paris Commission (PARCOM) and the Oslo-Paris Commission (OSPAR), and to identify trends in river water quality (Simpson, 1978). The twenty years of data (>360,000 data records) have been collected at 58 sites on the major river basins and include analysis of over 93 different determinants. The data on temporal trends have been linked to the Land Cover of Scotland 1988 in order to identify potential drivers of change. Correlations have been identified between some of the major land use types (urban, arable, and improved grassland) and current water quality variables (nitrate, phosphorus and suspended solids) (Figure 4).

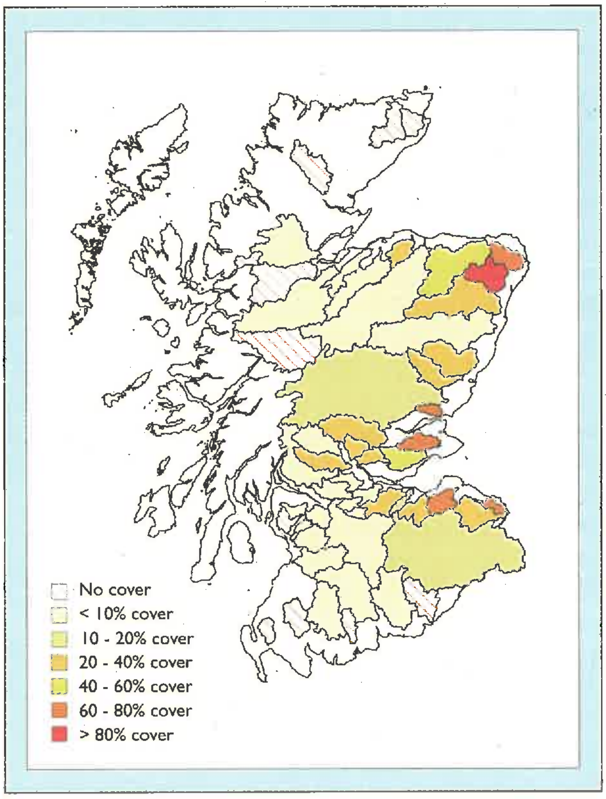

Figure 4. Distribution of arable land cover within the catchments of the Harmonised Monitoring Scheme.

Integration and scaling

The ability to develop modelling approaches through which we may extrapolate our understanding at the systems level to that of the catchment, region, or continent involves invoking a balance between model complexity and data availability. The new generation of information systems and technological advances allow for the integration of both spatial and temporal datasets, and such approaches have been the focus of management decision support systems within the catchment management programme.

The lack of soil hydrological data such as soil moisture retention and hydraulic conductivity has been a major impediment in using specific soils information into hydrological modelling. Given the costs and time necessary to obtain sufficient data on these highly variable soil properties, it is unlikely that this situation will be remedied in the near future. It is clear therefore, that other methods need to be employed in order to either generate these data or to develop hydrological models which have less rigorous data requirements.

Pedotransfer is the process by which complex and costly soil properties such as hydraulic conductivity can be generated from more easily measured (and so, generally more available) soil properties such as soil texture. A collaborative EU funded project (*Using existing soil data to derive hydraulic parameters for simulation modelling in environmental studies and in land use planning* ~ CHRX-CT94-0639) in which MLURI staff played a major part, has attempted to derive such pedotransfer functions from data stored in the HYPRES database. To date, both class and continuous pedotransfer functions have been derived for a range of soil textures and have been applied at the European scale. The experience gained in this project will be used in the development of similar functions more applicable for use in Scotland and incorporating a wider range of the more readily available soil information held within the Scottish Soils Database held at MLURI.

Under a three year NERC/SOAEFD collaborative research grant (Large Scale Processes in Ecology and Hydrology), catchment management scientists at MLURI, Aberdeen University, Institute of Hydrology, and the Scottish Environment Protection Agency (SEPA) have focused on modelling water quality at the large river basin scale (River Dee, NE Scotland). The specific emphasis has been the development of a set of mathematical modelling approaches which are robust, simple, and readily transferable to other catchment systems. To meet this objective a model which can simulate changes in water quality variables with flow at the sub-catchment ($<10km^2$) to catchment scale ($>1500km^2$) has been developed (Wade *et al.*, submitted) (Figures 5 & 6).

The extrapolation of our understanding of catchment functioning to the larger spatial units of landscape, region, and continent involves collaboration with a number of research groups in Europe and North America. The European DYNAMO Project (*Dynamic models to predict and scale up the impact of environmental change on biogeochemical cycling ~ ENV4-CT95-0030*) aims to predict and scale up the impact of environmental change on biogeochemical cycling using a variety of dynamic mathematical models. Models such as the dynamic MAGIC/MAGIC-WAND framework are being integrated in a GIS environment and are being used to scale up in space from the detailed site to regions, and to scale up in time from responses observed over several years to predict future impacts over the time periods of decades to centuries. This research is part of the EU TERI Programme (Terrestrial Ecosystems Research Initiative) and is designed to address strategic environmental issues, and uniquely aims to bridge the gap between research science and the requirements of European Environment Policy. For example, the DYNAMO programme has successfully integrated climate change and N deposition responses into predictive regional dynamic models.

Figures 5 & 6. Different faces of the River Dee.

Future Developments

Research will continue to focus on the determination of the hydrological and hydrochemical factors which are responsible for the movement of pollutants and nutrients into the freshwater and estuarine environments. The underpinning strategic science base will continue to be on issues of transport and scaling (Figure 7).

The focus for spatial model development will be the integration of physical transport mechanisms with process based representations of biogeochemistry. This will operate at a number of spatial scales, and will determine the dominant factors influencing the prediction of responses observed at the field or sub-catchment scale to that of the river basin. The interactions between model complexity and data availability will be crucial to assessing uncertainty in modelling approaches and scenario predictions.

The fate of atmospheric derived nitrogen to sensitive upland natural and semi-natural systems will involve the assessment of the relative magnitude, characterisation, and impact of losses of organic carbon, nitrogen and phosphorus from terrestrial systems. This will be mirrored by developments in risk assessment methodologies such as critical loads and the dynamic modelling of ecosystems at risk, to determine the time scale of impaction and/or recovery.

Geochemical controls, surface - groundwater responses, and the determination of particulate transport through erosion and sediment interactions will be linked to our understanding of solution transport and related to land use and management. The development of catchment based Spatial Decision Support Systems will aim to provide mechanisms for the pro-active and sustainable management of land and water resources.

Relevance to End Users

The Atmospheric Deposition, Land Use and Water Quality Management Programme has been closely involved in the assessment of anthropogenic impact of atmospheric deposition and land management on soil and water quality. The programme contributes directly to the DETR/SOAEFD Programme on critical loads, both through the mapping and modelling of impacts,

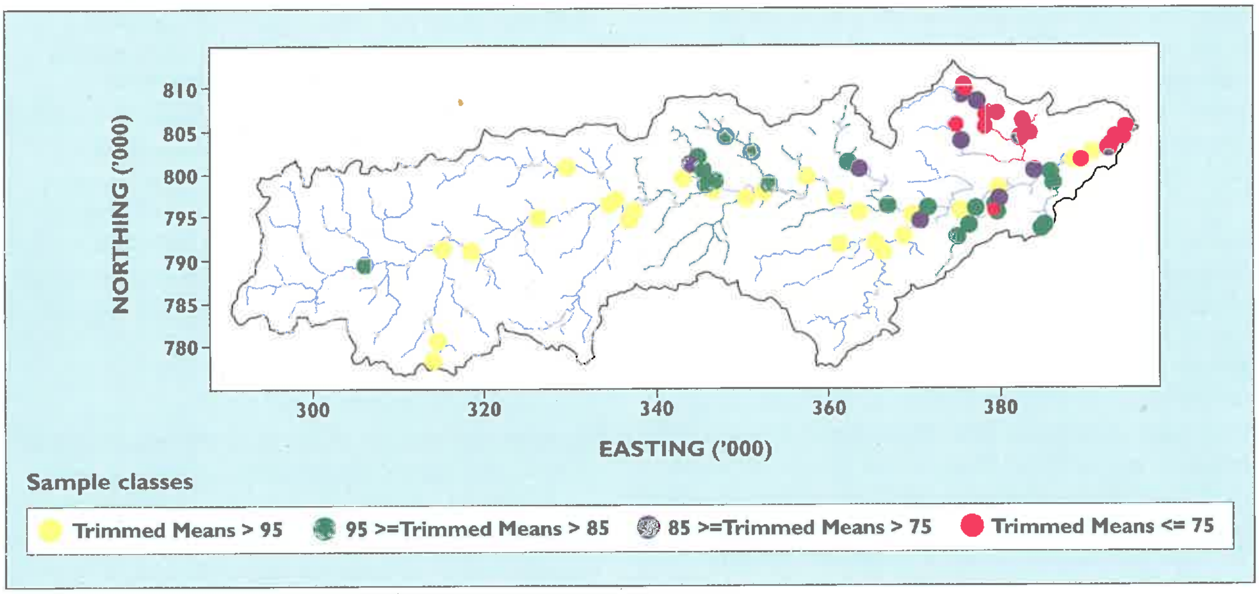

Figure 7. Water Quality Index (percentage) for the River Dee.

responses, and rates of recovery. The critical appraisal of the PROFILE model (used throughout Europe in critical load assessments), was undertaken on behalf of National Power - Powergen and outputs from this project have allowed for the determination in uncertainty calculations.

Recently SEPA undertook an assessment of the Standing Waters of Scotland, and as part of this project MLURI was commissioned to develop a methodology by which to determine the change in nutrient status of 170 lochs and to classify these into one of four different sensitivity bandings. This methodology has been further developed and has been utilised in more detailed catchment studies, including SNH funded projects on the Lunan Lochs (Perthshire) (Ferrier *et al.*, 1997), and the development of a catchment management assessment for Loch Davan (NE Scotland) (Davies *et al.*, 1997). The second phase of this latter project included a socio-economic assessment of potential remediation measures proposed for the loch and its catchment (Macmillan *et al.*, 1998).

Numerical methodologies developed to elucidate the signals contained in long term water quality datasets, have been used in a SNIFFER (Scotland and Northern Ireland Forum for Environmental Research) project to assess the impact of historical changes in atmospheric deposition at Loch Dee in SW Scotland (Langan *et al.*, 1997). MLURI, the Institute of Hydrology and BioSS have also invoked similar methodologies in their recent review of the Harmonised Monitoring Scheme in Scotland which has been involved in data collection since 1974, on behalf of the SOAEFD Environmental Protection Unit (Ferrier *et al.*, 1998).

Internationally, scientists involved in the programme are involved in proposed projects in India and in Sri Lanka. Collaborative studies also include links to Korea and China, and within the countries of Europe and North America.

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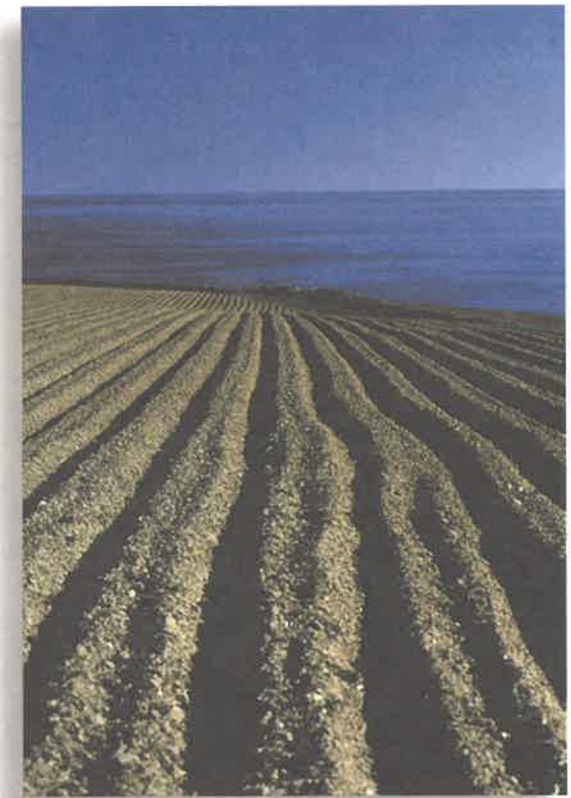

We seek to address the underlying scientific rationale associated with the definition of soil quality, alongside the changes in quality likely to arise from the increasing utilisation of wastes on land and the impact of pollutants.

Soil Quality, Contaminated Land and Waste Utilisation

Environmental protection has a key role to play in national (DoE, 1994) and international strategies (UNCED, 1992) aimed at sustainable development. Of the three environmental media, soil, air and water, soil has received the least attention (Royal Commission on Environmental Pollution, 1996), despite the fact that it performs a crucial role with respect to the future sustainability of land use systems (Pieri *et al.*, 1995) and in the responses of the other media, air and water, to environmental change. It is for this reason that work under the theme 'Sustainable Management of Soils' seeks to address the underlying scientific rationale associated with the definition of soil quality alongside the changes in quality likely to arise from the increasing utilisation of wastes on land and the impact of pollutants.

Quality standards have been readily accepted for air and water but it has proved more difficult to develop and apply such concepts to soils. There are a number of practical and conceptual difficulties. At a practical level, it is not easy to assess a complex material, such as soil, which exhibits considerable variability at a range of spatial and temporal scales. On a conceptual level, it is the multifunctionality of soil in the environment (Blum, 1993) which presents difficulties because soil is used for

- Plant growth and crop production, for food, fibre, timber or energy.
- Protection of surface and ground waters, by buffering, filtration and transformation of pollutants.
- Forming an important habitat for soil-dwelling micro- and macro-biota, thus safeguarding major biogeochemical cycles and an extremely diverse gene pool.

Soil quality has been identified as a key indicator in the 'UK Strategy for Sustainable Development'. Current indicators (DoE, 1996) are largely based on soil composition and, as such, there are a number of difficulties associated with their development and use. These include;

- Implicit assumptions as to the function of soil; for example, the inclusion of organic matter content as a soil quality indicator reflects its importance in the structural stability of mineral soils used in arable production systems but is of less relevance in the extensively managed, highly organic soils in the uplands of the UK (Figure 1).
- Difficulties in relating compositional change to soil processes; for example, high concentrations of heavy metals may be interpreted as an indicator of high risk whereas it may indicate that the metals are tightly bound and largely unavailable.
- The requirement to relate chemical presence to biological impacts; for example, the pollutant loading at which damage to soil function occurs will vary with the chemical form of the pollutant, the interactions with the soil matrix, and the nature of the target organisms.

Many definitions have been proposed for soil quality but, in view of the diversity of ecosystems the range of land uses and the contrasting soil types within Scotland, the definition given below is the most appropriate.

Soil quality is the capacity of soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health.
(Doran and Parkin, 1994)

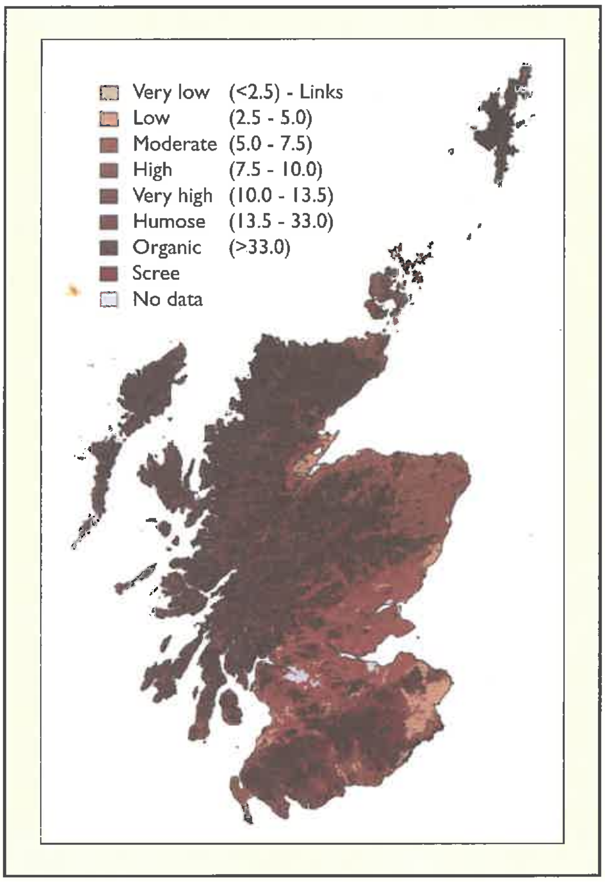

Figure 1. Organic matter content of surface horizons of Scottish soils.

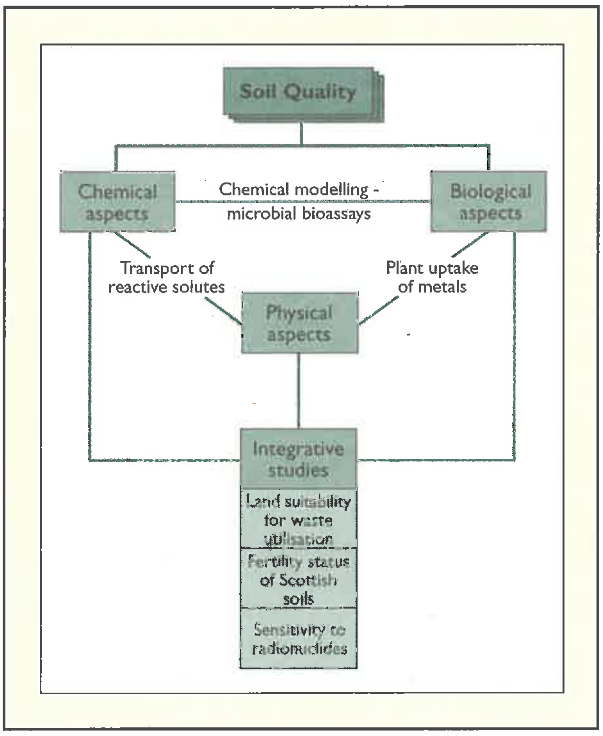

Figure 2. Programme structure and inter-disciplinary activities.

Strategic Objectives

The Royal Commission on Environmental Pollution have provided a valuable summary of the major stresses and interactions between land use and management and soil quality in the UK (Sustainable Use of Soil, Royal Commission on Environmental Pollution 19th Report, 1996). These include the impact of agricultural management practices on both mineral and organic soils, the risks and benefits of applying wastes to agricultural land and the safe management and re-use of contaminated land.

Our programme aims to provide a sound scientific understanding of the soil processes involved as well as a mechanism by which this knowledge may be transferred to end-users for inclusion in management protocols at field and site scale and for policy evaluation at national scale. Thus, we are concerned with the;

- Development of process-based indicators of soil quality in an agricultural and natural heritage context, in concert with objectives within the programmes dealing with Atmospheric Deposition, Land Use and Water Quality Management, (PU23) Land Use Options for Plants (PU26) and Soil-Plant-Animal Interactions (IPU36).
- Assessment of the impacts of waste utilisation on agricultural land at regional, catchment and process scale, thus contributing to a SOAEFD-funded co-ordinated programme on Waste to Land and to the development of farm-scale models for waste utilisation in the programme dealing with Geographical and Resource Analysis Programme, (PU21).
- Prediction of soil sensitivity and resilience to the presence of contaminants, such as potentially toxic elements, where the development of microbial techniques such as single carbon source utilisation have been taken up and utilised within other projects (e.g., MICRONET) in Land Use Options for Plants Programme, (PU26).

Technology transfer to a range of end-users is addressed within the structure of the programme (Figure 2) by considering these issues at a range of spatial scales as well as through participation in national advisory groups, publication in specialist and trade journals and the development of computer-based models.

Specific Objectives

Process-based studies

- Measure the changes with time of the chemical associations of the heavy metals in grassland and forest soils likely to receive sewage sludge.
- Predict the effects of mineral-humic interactions on metal retention by soils using thermodynamic models.
- Determine the extent to which the physical distribution of metal-contaminated sewage sludges influences plant uptake of pollutants.
- Assess the influence of clay mineralogy on soil structural stability and the release of mobile colloids from soils.

- Quantify the impact of dissolved and particulate organic matter, derived from farm animal wastes, on soil drainage water.
- Combine physical and chemical processes within a single modelling framework so as to allow prediction of diffusive-convective transport of reactive solutes in soils.
- Study the impact of heavy metals on biochemical and chemical processes influencing the plant availability of phosphorus from organic wastes.
- Measure the effects of sewage sludge applications to agricultural soils on soil microbial activity and the implications for agricultural productivity and long term soil fertility.
- Assess soil ecosystem recovery in relation to organic pollutants and heavy metals.
- Appraise the utility and validity of microbial indicators of soil quality and assess their relationship to other environmental factors.

Integrative studies

- Assess the factors and processes responsible for recent trends in the fertility of Scottish soils.
- Model the opportunities and constraints associated with organic waste recycling on land from a spatio-temporal perspective.
- Quantify the sensitivity of Scottish agricultural and land use systems to atmospherically derived radionuclide pollution.

Description of the Programme

The complexity of the soil environment requires that a wide range of scientific disciplines are used in order to understand the processes taking place and to assess the impacts of environmental stress caused by wastes and pollutants. Thus, the relationships between, and integration of, chemical, physical and biological aspects of 'soil quality' is a key feature of our programme.

Chemical aspects

Many of the chemical processes studied centre on the impact of potentially toxic elements (PTEs), such as Pb, Cu, Zn, Cd and Ni derived from wastes and other sources, on soil quality. This is being addressed experimentally using novel approaches, such as the incorporation of stable isotopes of Pb, Cu, Zn, Cd, and Ni in soil followed by sequential dissolution to assess the association between the metals and soil components. These interactions are also being studied by chemical modelling. Particular emphasis is placed on how to represent soil components, such as iron oxides and humic materials within a range of widely used models, such as WHAM (Tipping, 1994), MINTEQ (Felmy *et al.*, 1984) and MINTEQA2 (Allison *et al.*, 1991), although with the development of ORCHESTRA (see later) attention is now being focused on its development. Chemical modelling is also being used to link chemical processes and biological impacts, as measured by microbial bioassays. These assays will be utilised in the second phase of the Sewage Sludge Network project which is a major collaborative project involving ADAS, Rothamsted, Water Research Centre and SAC, jointly funded by SOAEFD, MAFF, DETR and UKWIRL.

Physical aspects

The influence of the physical distribution of pollutants within the soil on plant uptake is being studied using both pot experiments and laboratory studies where it has been shown that incorporation of sewage sludge results in greater metal uptake than the same metal loading applied to the surface. The development of an entirely new modelling framework, ORCHESTRA (**O**bject **R**epresentation of **CHE**mical **S**peciation and **TRA**nsport) has provided an extremely flexible and valuable tool with which to link chemical and physical processes within the same model (Meeussen *et al.*, 1996). This is being used to simulate the transport of reactive chemicals, such as phosphate and sulphate, within the soil. Colloid transport can also be modelled which will ultimately permit the integration of experimental work on the effects of clay mineralogy on soil structural stability and the influence of animal slurries in the supply of organic colloids implicated in major nutrient transfers from land to water.

Biological aspects

Over 50% of the land area of Scotland is covered with organic soils which are used in extensive management systems aimed at natural heritage as well as agricultural and forestry objectives. In these soils microbial processes play a key role in carbon turnover and in driving major nutrient cycles and we are developing microbial indicators of soil quality for these systems. This work is based on two complementary approaches. The first involves the measurement of substrate quality for microbial activity through direct measures of respiration rates, as an indicator of carbon turnover, and its relationship to chemical properties as revealed by spectroscopic methods. The second is concerned with the response of the microbial community itself and deploys many of the approaches developed for the measurement and assessment of changes in microbial diversity in response to environmental stress, such as pollution by heavy metals. This has been shown to result in significant changes in the composition of the microbial community and the ability of organisms to catabolise aromatic hydrocarbons - an observation which is now being used to study the reversibility of ecosystem damage by heavy metal pollution.

Integrative studies

Work at national and regional scale forms an important component of our technology transfer strategy. It is based on our ability to develop new perspectives on land use issues through a combination of process-based knowledge of soils, developed both within this programme and others in the Institute, with the soil, landcover and climate datasets, being integrated within the programme dealing with the Development of Decision Support Systems (IPU38). Initially, work on waste utilisation was based on a rule-based approach but, increasingly, process-based knowledge is being incorporated in order to assess soil sensitivity to heavy metals (Towers and Paterson, 1997). These approaches are now being extended for a wider range of wastes to include a temporal component. An alternative approach is being developed to identify major nutrient surpluses arising from current management practices through a combination of agricultural census data, obtained on a parish basis, with soil and climate datasets (Domburg *et al.*, in press). Finally, the process-based studies on radiocaesium contamination are being interpreted within the context of key processes (Dumat *et al.*, 1997; Cheshire *et al.*, in press) which are in turn being related to spatially resolved soil attributes.

Achievements

- Development of an improved procedure for the quantification of reducible components in the EU Standards, Testing and Measurement sequential extraction method.
- Representation of 'real soils' in modelling the interaction of specifically-adsorbed anions.
- Completion of Phase 1 of the National Sewage Sludge Network project and the establishment of a field resource at Hartwood Research Station for future impact studies.
- Demonstration of how sludge incorporation in topsoils increases metal uptake by plants compared to surface applications of the same metal loadings.
- Completion of new generic, object-oriented modelling tool, ORCHESTRA, which allows the representation of user-defined chemical and physical processes within computer models.
- Elucidation of the role of lithogenic factors in the presence of dispersion-resistant aggregates in Scottish soils.
- Establishment of a new SOAEFD co-ordinated programme and collaborative project with SAC on waste utilisation on land.

Current Research

In Scottish land use systems the soil resource performs two key roles - as a component of arable and mixed farming systems which are carried out on less than one fifth of the land surface and as a component of hill and upland systems where extensive agriculture, forestry and natural heritage aspects predominate. Concepts of soil quality must be developed for both of these situations and must also be applicable to other issues which impact on the sustainable use of soils, such as the utilisation of wastes on land and the entry of pollutants into the soil environment.

Pollution can impact adversely on every aspect of soil quality and both experimental and modelling approaches are required in order to address the main issues. Our involvement with the EC Standardisation, Measurement and Testing (SMT) programme (Quevauviller *et al.*, 1997) has been maintained and, indeed, increased over the past year with two main projects - the first dealing with improvements to sequential extraction procedures, which are widely used in the characterisation of contaminated soils, and the second addressing the issue of sampling strategies for contaminated land. Preliminary data from a study of the current sequential extraction procedure has indicated that the method considerably underestimates the reducible fraction and, thereby, overestimates the oxidisable and residual fractions. Modifications to the procedure are now being developed to overcome this difficulty and the extraction procedure is now being used within an experiment designed to trace the redistribution of added metals between various soil components and to assess the dynamics of redistribution.

Chemical modelling plays a key role in our programme. In relation to deriving model inputs from generally available soil parameters, soil oxalate extractable Fe and Al, were used successfully to develop a model description of molybdate adsorption by eight Scottish soils (Lumsdon, submitted). The results from this study reinforce the view that a major effort is required in order to accommodate the role of organic matter in adsorption processes. Work is currently being carried out in collaboration with colleagues from the Department of Soil Science and Plant Nutrition in Wageningen University. To date, new experimental data for the adsorption of fulvic acid by goethite has been obtained and the results have been used to develop a chemical model that describes the pH and ionic strength dependency of fulvic acid adsorption by goethite.

One of the major threats to the sustainable use of soil in arable systems is deterioration of soil structure due to inappropriate or ill-timed management. This can result in either enhanced loss of particulates by water erosion or compaction of the soil with concomitant impacts on biological activity. The role of particulates as a potential mechanism for transfer of major nutrients and pollutants from soil to water (Maguire *et al.*, in press) is being addressed within the Atmospheric Deposition, Land Use and Water Quality Management Programme (PU23) but, within the Soil Quality, Contaminated Land and Waste Utilisation Programme (PU24), attention is focused on the mechanisms by which particle detachment occurs and whether there is a link to the nature and properties of the predominant clay minerals in the soil. Many studies have demonstrated the importance of organic matter in the stabilisation of soil structure (Lal and Pierce, 1991; Zhang *et al.*, 1996) and attempts have been made to define critical thresholds of organic matter content below which the risk of structural deterioration increases (Federoff, 1987). In order to assess the feasibility of this approach an examination of other factors that may play a role in aggregate stability has been undertaken. A range of soils, developed on different parent materials, has been examined by gas-adsorption and mercury porosimetry and it has been shown that some of these soils, developed on particular parent materials, contain dispersion-resistant aggregates that are not associated with organic matter. Clearly, this points to a requirement for soil-specific guidelines for critical levels of soil organic matter to protect structural stability.

Surface applications of sewage sludge can result in high concentrations of potentially toxic elements at the soil surface which increases the risk of animal ingestion of PTE-contaminated soil and hence of PTE uptake into the food chain. Incorporation has the advantage of reducing metal concentrations at the surface even though the overall loading remains the same as for surface applications. Laboratory and glasshouse experiments have been carried out to examine the impact of the method of application and it has been

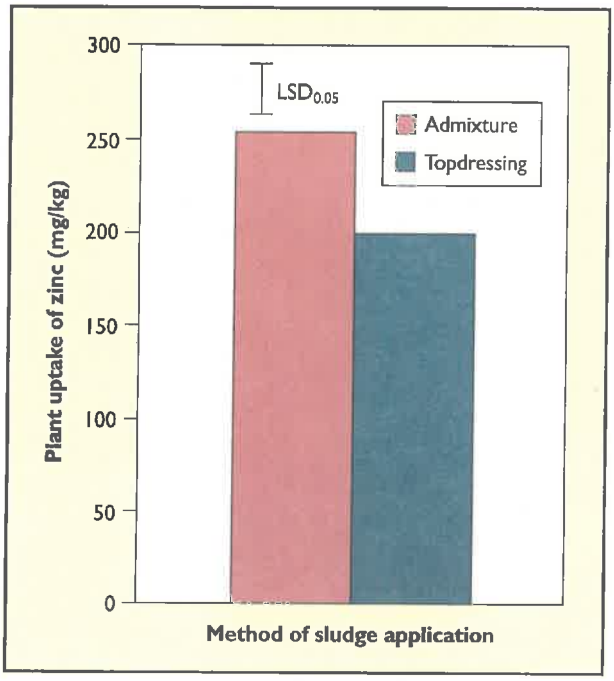

Figure 3. Influence of method of application of sewage sludge on zinc uptake by ryegrass.

shown that incorporation results in increased uptake of metals by the growing plant (Figure 3). Work in this area is now being directed towards the potential interactions between phosphorus, one of the major nutrients in sewage sludge, and heavy metals in order to assess whether availability and/or toxicity are moderated by chemical reactions.

Adsorption on oxide components is a key process governing the behaviour of phosphate in mineral soils (van Riemsdijk, 1996). Using a new object-oriented modelling framework (ORCHESTRA), the importance of transport processes in determining phosphate availability has been demonstrated and the potential impact of plant exudates on phosphate mobilisation has also been modelled (Figure 4)in collaboration with Wageningen Agricultural University. In contrast to the behaviour of P in mineral soils, where chemical and mineralogical factors are dominant, P supply in nutrient-poor acid soils, rich in organic matter, may be more dependent on the hydrolysis of organic forms by mycorrhizae and transport to the plant roots. Nuclear magnetic resonance (NMR) spectroscopy has shown that P in organic soils is involved in a wide range of reactions including bridging to humic acid *via* aluminium species (Bedrock *et al.*, 1997a). The behaviour of nitrogen in both mineral and organic soils is largely dependent on biological and physical processes. For example, in an EU-funded project with collaborators in Denmark and Portugal, it has been shown that fungal, rather than microbial, decomposition of incorporated straw dominates (Bedrock *et al.*, 1997b). Although the rate of decomposition of straw was similar in both cool and warm climates, there were wide differences in the immobilisation of N, between 6 and 10 kg/ha in Scotland but only between 1 and 3 kg/ha in Portugal, and clearly nitrogen conservation by straw incorporation is more appropriate under Scottish than under Portuguese conditions (Cheshire *et al.*, submitted). Work on the behaviour of nitrogen is closely co-ordinated with that taking place elsewhere in the programme, particularly in the programme dealing with Atmospheric Deposition, Land Use and Water Quality Management (PU23).

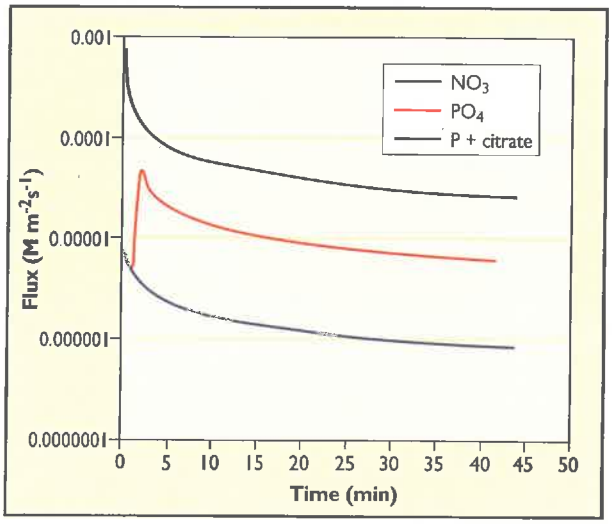

Figure 4. Modelled fluxes of nitrate and phosphate to plant roots using ORCHESTRA.

No assessment of soil quality would be complete without considering the biological and, more specifically, microbiological factors. New research, using two distinctive but closely co-ordinated approaches, is focused on the organic soil resource. The first is aimed at assessing the quality of the soil resource itself as a substrate for microbial activity. A number of soil biological parameters have been suggested as possible indicators of soil quality, notably microbial biomass carbon and basal respiration, and these have been incorporated into national and international programmes. Carbon dioxide is the major product of aerobic processes and so CO_2 output from soil integrates all the processes within the C cycle and can be expressed in a number of ways - basal respiration, metabolic coefficient and substrate induced respiration. For example, peat respiration may be used as an indicator of peat quality and recent work has shown a relationship between oxygen uptake and the C/N ratio and infra-red absorption characteristics of the peat (Figure 5). Multivariate statistics are now being employed to improve upon these predictive indices.

New approaches for measuring the functional diversity of microbial populations have been developed and tested (Campbell *et al.*, 1997) in a range of studies looking at impact of pollution on soil quality. These have been deployed in relating management and vegetation cover to soil microbial diversity within the MICRONET project. The use of this approach to construct community level physiological profiles of soil microbial communities has been applied in a wide variety of collaborative projects including the study of the impacts of elevated CO_2 on rhizosphere populations (Hodge *et al.*, in press) and the effects of atmospheric N deposition (Johnson *et al.*, submitted).

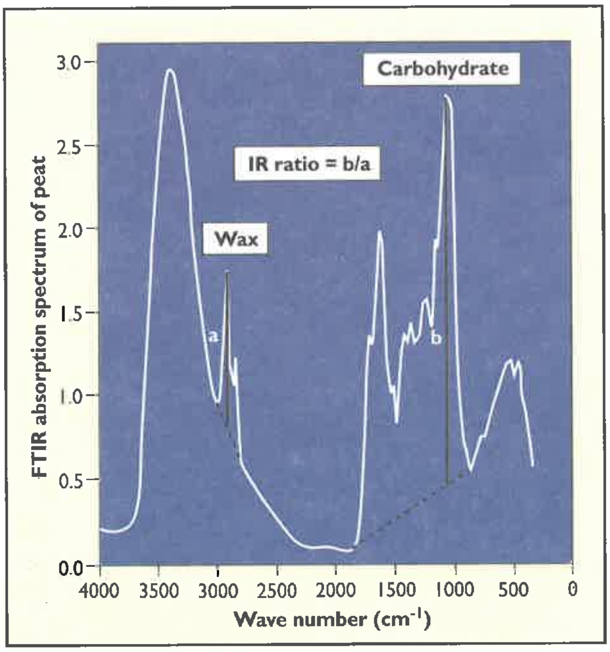

Figure 5. Fourier Transform infra-red spectrum of peat showing components used in determining 'quality index'.

Changes in fungal diversity may also be of considerable importance for C turnover in the ecosystems associated with organic soils but there far fewer methods for its quantification and we are undertaking a review of the utility of molecular biology techniques.

Concerns about the impact of potentially toxic elements (PTEs) on soil quality are widespread throughout Europe and have resulted in a number of different soil protection approaches within European countries (Visser, 1994). Many of these, such as that encompassed in the Sewage Sludge Regulations in the UK (DoE, 1989), are based on the measurement of 'total' contents of PTEs, which have also been included as soil quality indicators by DETR in the UK Sustainable Development strategy. However, in order to assess risk, it is the reactivity and mobility of the PTEs that is important and, therefore, the amount of metal that can be bound by soil components must be assessed. A site based assessment developed for mineral soils has been extended to include organic soils and has been applied to the soil profiles held in the National Soils Inventory (Paterson *et al.*, 1997). On the basis of metal content alone lead has been shown to be the most significant contaminant in Scottish soils but if attention is focused on the binding capacity of soils then the potentially greater mobility of zinc gives more cause for concern and two quite different pictures of the threat of heavy metal pollution to soil quality in Scotland are obtained (Figure 6). Experimental work is now under way to validate and refine this approach. It is clear that there is a need for

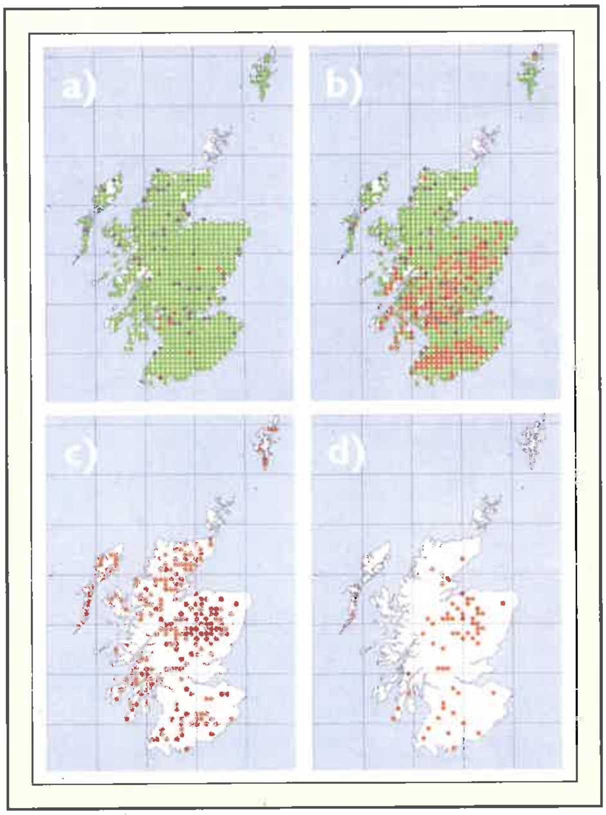

Figure 6. Comparison of soil quality indicators based on metal contents with those from binding capacities for Zn (c) and Pb (d).

further understanding of the mechanisms by which metals are held in organic soils.

The use of bioassay organisms has proved to be useful for the direct toxicity assessment of metal-polluted soils (Bundy *et al.*, in press) and may be a more relevant method of detecting toxic concentrations in soil pore waters than chemical analysis. Single species assays have been used in conjunction with chemical speciation modelling to examine the relationship between metal speciation and toxic responses. Experiments using metal solutions and well defined complexant agents showed that toxicity to lux-modified bacterial constructs was not related to the total metal concentration but was more closely related to the free-ion model of toxicity. The chemical species predicted by modelling did not, however, explain all of the toxic response suggesting that our view of bioavailability of metals in soil pore waters may need refining.

Work on radionuclides is now being drawn together in the form of a risk assessment of the sensitivity of Scottish land use systems to radionuclide pollution. This has involved completion and publication of work illustrating the important role played by micaceous clay minerals, even in highly organic soils, on the fixation of caesium (Cheshire *et al.*, in press). In addition, the ability of soils to adsorb caesium has been shown to change significantly upon selective removal of various mineral and organic matter fractions, e.g., the removal of organic matter increases the uptake of caesium by clays while the destruction of mineral matter in the humic fraction of soils affects the Kd values showing that only exchangeable sites remain (Dumat *et al.*, 1997). The aim of current work is to identify key soil attributes and appropriate spatial information carriers to produce the risk-based assessments on national scale.

Future Developments

Sustainable development will remain a key issue at international, national and local levels for the foreseeable future. While HM Government has indicated its desire to concentrate attention on relatively few 'headline indicators' there is also an acceptance that, for the indicator concept to be robust and have scientific validity, a framework will be required within which more detailed, process-oriented indicators will be deployed. The most recent report from the Round Table on Sustainable Development has suggested that indicators are required for five 'areas of crucial importance' whilst the DETR Indicators sub-group has identified a sixth in the 'management of renewable resources'.

- Management of renewable resources
- Consumption of non-renewable resources
- Pollution of air, water and land
- Landscape and cultural resources
- Biodiversity
- Social issues

The work which is being carried out within this programme unit addresses many of these key areas, particularly management of renewable resources, pollution of soil and microbial biodiversity, and will have implications for landscape and cultural resources.

Specifically, our principal long-term aims will be to:

- Understand more fully the relationship between land use and management in such a way that we can develop soil quality indicators that reflect and integrate key chemical, physical and biological processes. This work will target areas of land which have undergone land use change e.g., agriculture to forestry and seek to identify the soil changes, particularly those relating to organic matter turnover, acidification, microbial changes and mobilisation of heavy metals.
- Identify more explicitly the risks and benefits associated with the application of wastes to land, particularly those which impact on soil quality indicators associated with the dynamics of organic matter in soils. As well as the major integrative effort to be applied in a joint project with SAC to assess the feasibility of developing a spatially based decision support tool to aid in waste utilisation strategies, we shall also be examining the soil microenvironments that have developed after plant growth in a sewage sludge treated soil and seek to reconcile any changes with the spatial distribution of roots and pollutants.
- Integrate experimentally based investigative tools and chemical and transport models with a view to improving the theoretical rigour of operationally defined fractionation of contaminated soils. This will build on a successful MSc project carried out jointly with Edinburgh University in which chemical modelling was used to assist in the interpretation of analytical results from selective extraction techniques.
- Seek to contribute, within the UK and Europe, to the development of a critical loads methodology for potentially toxic elements and hence identify appropriate environmental quality standards for soils. In particular, we shall focus our attention on organic soils, which are a significant component of the soil resource of Northern Europe. These soils are frequently associated with rare ecosystems and habitats, which are critically dependent on the existence of relatively pristine environments, and long range transport of pollutants may seriously impact on both biota and biogeochemical cycles within these extensively managed or semi-natural systems. In addition, the Chernobyl nuclear accident demonstrated clearly that impact models developed for mineral soils cannot be simply transported to organic soils.

Thus, the programme will serve as an important part of the Institute's overall research strategy in relation to the sustainable management of the soil resource.

Relevance to End Users

In relation to soil quality three groups of end-users may be clearly identified. The first of these is national government, who are now undertaking a major revision of the UK Sustainable Development strategy. An important part of this strategy is the identification of indicators of sustainable development and we have been involved in the Soil, Countryside and Landscape Indicators Group. The principal task of this group is to suggest a series of indicators, which are scientifically robust, have resonance with end-users and where, preferably, data sources already exist which will enable targets to be set. The second group are agencies of government, such as the Scottish Environmental Protection Agency (SEPA), where we also serve on a committee developing indicators for Scotland and Scottish Natural Heritage (SNH), for whom we have recently completed a report on the incorporation of soil indicators in their Integrated Monitoring Programme. Finally, the development of process-based indicators at appropriate spatial scales will enable land users to set management targets to sustain the use of the soil resource.

In the area of waste utilisation on land we are joint co-ordinators with SAC of the SOAEFD co-ordinated research programme 'Waste to Land'. One of the principal aims of this programme is the direct involvement of end-users and, to this end, we have formed a Steering Group composed of representatives from the Water Authorities, SEPA, SNH, the farming community and the Scottish Office Agriculture Department and the Environmental Protection Unit. In addition, within the Sewage Sludge Network project we play a significant role as managers of one of the two Scottish sites and participate in Funders Group meetings which involve MAFF, SOAEFD, DETR and UKWIRL. In addition, through our MRCS activities we are seeking to solve the problems of clients from a range of industries who are concerned with the safe disposal of contaminated wastes.

Finally, in the area of contaminated land a recently completed MRCS project on behalf of a major chemical company on the pathways by which contaminants may be mobilised from a disused industrial site has now led to the award of a NERC URGENT award with Edinburgh University and other colleagues. Our consortium includes a representative from a major international environmental consultancy, Dames and Moore, as well as direct contact with the responsible local authority. Our role in this project will be the development of user-defined software tools to model the transport of reactive contaminants in soils, where ORCHESTRA will be used to deliver a species-specific model which will address the impact of remediation treatments on Cr-contaminated sites.

Our involvement with end-users serves two purposes; on the one hand it is a mechanism by which we can play our part in maintaining the resource base of the Institute through a period of 'level funding' from central government but it also gives us, as research scientists, a context for much of our work and can highlight areas of difficulty where our knowledge and skills can be deployed to solve 'real world' problems.

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Developing management strategies for marginal lands in temperate climates, which balance productivity with environmental objectives, requires an understanding of the processes governing resource acquisition and growth of herbaceous and woody perennials.

Land Use Options for Plants

Marginal lands in temperate climates have soils which are often organic, and of low fertility and pH. These soils support two main kinds of ecosystems, natural and semi-natural pasture systems, and shrub, woodland and forestry systems which are dominated by trees. Developing management strategies for these systems, which balance productivity with achieving environmental objectives, requires an understanding of the processes governing resource (carbon and nutrients) acquisition and growth of herbaceous and woody perennials. This, in turn, requires an understanding of the interaction between the soils and plants of these systems, and the impacts of grazing animals. In studying the ecophysiology of resource acquisition and use by plants at a strategic level we are underpinning studies of vegetation dynamics and grazing ecology elsewhere in this theme.

The programme is in line with the recommendations of the Technology Foresight Panel on Agriculture, Natural Resources and Environment, which recommends that Integrated Ecosystem Management be a research priority. The output of our research will also contribute to the development of sustainable woodland and forestry management guidelines. These in turn support the development of sustainable forestry strategies, the need for which was highlighted recently by the Biotechnology Government Panel on Sustainable Development.

Strategic Objectives

In the low input systems which characterise marginal lands fertilisers are seldom used. Resource acquisition by plants is, therefore, governed by soil fertility due to the turnover of soil organic matter. The availability of nutrients in the rhizosphere, therefore, is determined largely by the activity of soil microbes. Because microbial growth and activity in soil is often carbon limited, nutrient availability in the rhizosphere is governed by the loss of carbon from plants as root exudates, root turnover and leaf litter. Any changes in the management of vegetation in these low input systems (such as an increase in grazing intensity) or environmental perturbations (such as nitrogen deposition or climate change) which affect the balance between carbon and nitrogen acquisition by plants, will in turn influence soil nutrient dynamics. Our aim, in both grassland and tree-based systems, is to understand these carbon/nitrogen interactions by considering whole-plant physiology in relation to soil fertility. Such an understanding will enable the consequences of different management strategies for low input systems to be assessed in the context of the processes governing plant growth and vegetation dynamics. The programme aims to understand the main ecophysiological processes regulating nutrient supply to, and use by plants for growth in extensive, sustainable systems on marginal lands.

Research in this programme is linked to studies of soil organic matter and soil microbiology in the Soil Quality, Contaminated Land and Waste Utilisation Programme (PU24). There is a close integration between our studies of the ecophysiology of grasses and the soil microbiology and chemistry in the Soil-Plant-Animal Interactions Integrated Programme (IPU36) which considers the diversity and activity of soil micro-organisms and the processes regulating nitrogen and phosphorus cycling in pasture soils, as influenced by grazing animals. Our studies of the ecophysiology of individual plants also underpins the Natural Heritage Management - Vegetation Dynamics Programme (PU27) by considering the impact of management on plant competitive interactions.

Hill and upland pastures

In order to develop strategies for the sustainable management of hill and upland pastures it is important to understand how grasses respond to defoliation, in terms of their ability for both regrowth and competition with neighbouring plants. An understanding of the ecophysiology of grazed grasses at the level of the individual plant is needed to enable the development of process-based models of vegetation dynamics in extensively-managed pastures. Our research has been concentrating on processes important in determining the competitive ability of grasses subjected to grazing, by considering their relative ability for uptake or remobilisation of stored nitrogen to support regrowth following defoliation, and growth responses both above and below-ground. Root growth and morphology are particularly important in determining the ability of a grass species to take up nitrogen from soil after defoliation, particularly if the distribution of nitrogen is heterogeneous, as is the case in the low input systems we study.

Trees

Changing patterns of land use are resulting in trees being grown in a wider range of land use systems, including farm woodlands, coppice systems, long rotation set-aside, and the reintroduction of semi-natural woodland. In such systems of land use fertilisers are seldom applied. The majority of nutrients used for growth, therefore, come from the decomposition of soil organic matter and leaf litter by soil microbes and the internal cycling of nutrients. Traditionally knowledge of managing such systems comes predominantly from the study of plantation forestry. However, at the Macaulay we are studying the processes of internal cycling of nitrogen in order to develop management strategies for a range of tree-based systems to enhance nitrogen storage and remobilisation for tree growth. We are also studying interactions between tree carbon and nitrogen status on assimilate partitioning and growth. Finally, we are determining the long-term impacts of harvesting techniques on the establishment and growth of plantation forests. This work aims to develop Decision Support Tools for predicting site suitability for whole-tree harvesting for second rotation forestry.

Achievements

Ecophysiology of grasses

- Determining that an increased frequency of defoliation depletes the ability of grasses to remobilise stored nitrogen for regrowth, but has little effect on nitrogen uptake for supplying growing leaves (Thornton and Millard, 1997)

- Establishing that the response of root systems to defoliation depends upon both the morphology of the species and the nutrient status of the soil.

- Understanding how roots are able to colonise and utilise nitrogen patches in soil and the consequences of defoliation for nitrogen acquisition from a heterogeneous soil supply.

- Quantifying the effects of aluminium and pH on the response of *Lolium perenne* and *Deschampsia flexuosa* (which differ in their tolerance of low pH) to defoliation (Thornton, in press).

Ecophysiology of trees

- Developing and testing a method to quantify remobilisation of stored nitrogen by field-grown trees in the spring, by monitoring xylem sap amino acid translocation patterns (Millard, Wendler, Hepburn and Smith, submitted).

- Developing strategies to enhance the sustainable management of orchards through an understanding of the internal cycling of nitrogen in fruit trees (Tagliavini, Millard and Quartieri, in press; Tagliavini, Quartieri and Millard, 1997, Neilsen, Millard, Neilsen and Hogue, 1997).

- Quantifying the effects of drought and nitrogen supply on whole-plant carbon allocation in poplar (Ibrahim, Proe and Cameron, in press, submitted).

- Determining that whole-tree harvesting can reduce tree growth in subsequent rotations of Sitka spruce (Proe, Craig, Dutch and Griffiths, submitted; Proe, Dutch, Pyatt and Kimmins, in press).

Current Research

Ecophysiology of grasses

Remobilisation of nitrogen for leaf growth after defoliation has been studied in a range of species, often in response to a single defoliation when plants are used for forage, e.g., *Lolium perenne* (Ourry *et al.*, 1990; De Visser *et al.*, 1997), *Medicago sativa* (Kim *et al.*, 1993) and *Trifolium repens* (Marriott and Haystead, 1990). In grazed swards plants are subjected to repeated defoliation. Our work has, therefore, investigated the impact of repeated defoliation and has shown that plants become morphologically adapted and so respond differently to defoliation (e.g., Thornton *et al.*, 1993, Thornton *et al.*, 1994, Thornton and Millard, 1996).

We have determined the role of root uptake and remobilisation of nitrogen for leaf growth after defoliation of *L. perenne* and *Festuca rubra* plants which were morphologically adapted to defoliation and previously uncut (Thornton and Millard, 1997). In both species N uptake was unaffected by the frequency of defoliation. In previously uncut plants remobilisation provided 50% and 41% of N used for regrowth in *L. perenne* and *F. rubra*, respectively. However, in regularly defoliated plants little N was remobilised by either species. We conclude that increasing the frequency of defoliation resulted in a reduction in the growth rate

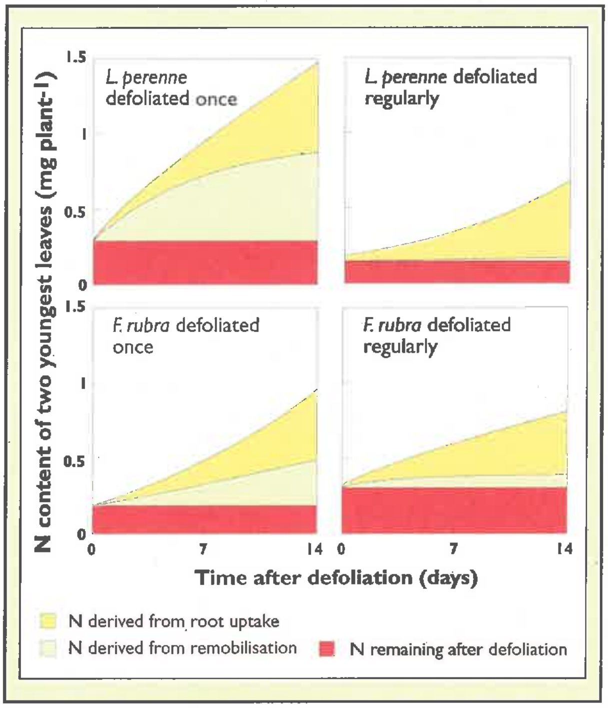

Figure 1. The contribution of nitrogen derived from root uptake or from remobilisation for the growth of Lolium perenne *and* Festuca rubra *after regular or single defoliation.*

of new leaves, due to a depletion in the capacity of the plants to remobilise stored nitrogen (Figure 1).

Defoliation affects the growth of roots as well as shoots. We have shown that grass species with thicker roots exhibit less plasticity in root biomass in response to defoliation but greater architectural plasticity. However, these responses can depend upon soil nutrient status because faster growing species such as *L. perenne* exhibit more branch development when nitrogen replete, whereas slower growing *F. ovina* develops most branches when grown with a poor N supply (Figure 2). Similar morphological adaptations to nutrient supply were also found in perennial grasses by Hubersannwald *et al.* (1996). Such characteristics of the root system are important in determining the ability of different species to utilise nutrient-rich patches in the soil and so compete for nutrients in the heterogeneous soils that characterise marginal lands. The response of roots to nutrient supply, therefore, is important in determining competitive interactions between plants which regulate vegetation dynamics. Previous studies have considered short term responses in grasses from a wider ecological range (Grime *et al.*, 1986) or very different vegetation types (e.g., Jackson and Caldwell, 1989). We have also collaborated with INRA, Lusignan, to study biomass allocation and root morphology in four contrasting grass species subjected to varying severities of defoliation.

Reduction of inputs to grasslands, especially lime, results in lower soil pH values. At low pH grasses are thought to be influenced by either the concentration of aluminium ions in the soil solution (Tyler, 1993), or both aluminium and hydrogen ions (Anderson and Brunet, 1993). In addition to effects of aluminium on growth (Delhaize and Ryan, 1995) uptake of a range of ions can be affected (Macklon and Sim, 1992), including ammonium (Nichol *et al.*, 1993) and nitrate (Rufty *et al.*, 1995). The effects of aluminium and pH on N remobilisation have not been studied before. We found that both *L. perenne* (less acid tolerant) and *D. flexuosa* (more acid tolerant) remobilised more nitrogen after defoliation at pH 3.5 and 5.5 than intermediate values (Thornton, in press), with the two species being similarly affected by both aluminium and pH with respect to the total nitrogen supplied to the leaves. The effects of aluminium and pH upon the supply of nitrogen to growing leaves after defoliation are not, therefore, dominant factors in the competition determining vegetation dynamics of grazed swards.

A new model has been developed for identifying allocation patterns in plants well adapted to continuous grazing, a management regime characteristic of marginal pastures (Figure 3). The

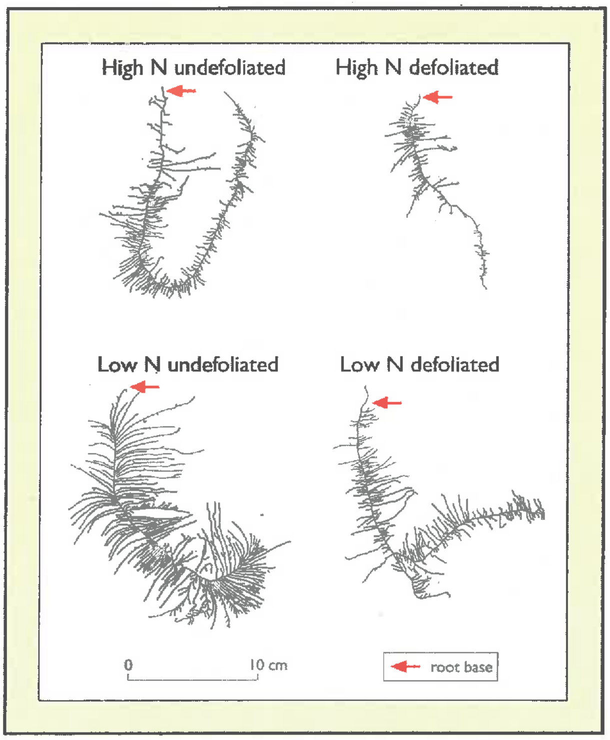

Figure 2. The effect of repeated defoliation under contrasting levels of nitrogen supply on the branching characteristics of roots of Festuca ovina.

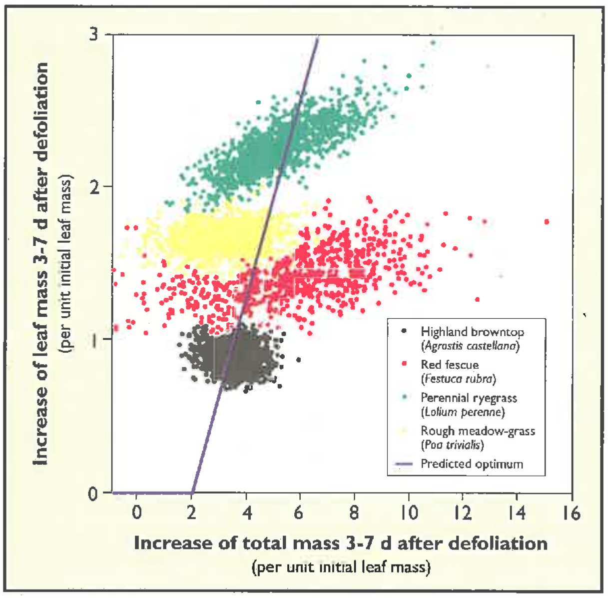

Figure 3. Comparison between observed allocation after defoliation and model predictions for four grass species.

modelling approach has been distinct from other models of allocation after defoliation, because it considers the trade-off between the availability of photosynthates and the exposure of leaf laminae to defoliation (Birch and Thornton, submitted). Most existing crop models have assumed fixed, empirically determined allocation patterns (e.g., McCown *et al.*, 1996; Asseng, Richter and Wessolek, 1997), constraining their use to individual species and making them unsuitable for simulating defoliation. Generic models allowing variable allocation have generally derived allocation patterns from assumptions about the physiological balances and processes in the plant (e.g., Hilbert and Reynolds, 1991; Thornley, 1995). The approach of this model has been more ecological, because it considers trade-offs relevant to competition between plants, such as in classic life history models (e.g., Cohen, 1971; Tilman, 1988). It is, therefore, well suited to simulation of selection of genetically determined allocation characteristics in a population.

Ecophysiology of trees

Uncoupling growth from nutrient uptake, by storage and remobilisation of nitrogen, allows trees to grow when the external availability of nitrogen is low (Figure 4). Such internal cycling is a major source of nitrogen used for seasonal growth of both deciduous and evergreen trees (Millard, 1996). Developing sustainable management strategies for trees requires N storage and remobilisation to be quantified in relation to management inputs, which until now has been difficult to achieve (Nambiar and Fife, 1991; Millard, 1996). Whole-tree nitrogen budgets are often imprecise and do not allow for nitrogen uptake in the autumn contributing directly to storage (e.g., Wendler and Millard, 1996) while ^{15}N can only be used to quantify N storage and remobilisation in small trees grown in sand culture (Millard, 1996).

An alternative method to quantify nitrogen remobilisation by trees has been developed, by studying their nitrogen translocation patterns in the spring. In a study of *Betula pendula* seedlings we found that ^{15}N remobilisation occurred immediately following bud burst while N derived from root uptake did not appear in the leaves for some 12 days. During N remobilisation there was a ten-fold increase in the concentration of N in xylem saps, due predominantly to increases in citrulline and glutamine (Millard *et al.*, submitted). A field experiment with five species of deciduous tree confirmed that for each species there was an increase in xylem sap nitrogen concentration following bud burst, due to nitrogen remobilisation. In each species a single amino compound was translocated as a consequence of nitrogen remobilisation (citrulline in *Alnus glutinosa* and glutamine in *Prunus avium, Populus erichocarpa, Crataegus monogyma* and *Acer pseudoplatanus*). This amino acid signature can now be used to assess the duration of nitrogen remobilisation by trees in the spring. Coupled with measurements of sap flow it might also be possible to calculate the amount of nitrogen translocated.

With our understanding of the processes of internal cycling of nitrogen in trees we have collaborated with groups in Italy and Canada to develop strategies for

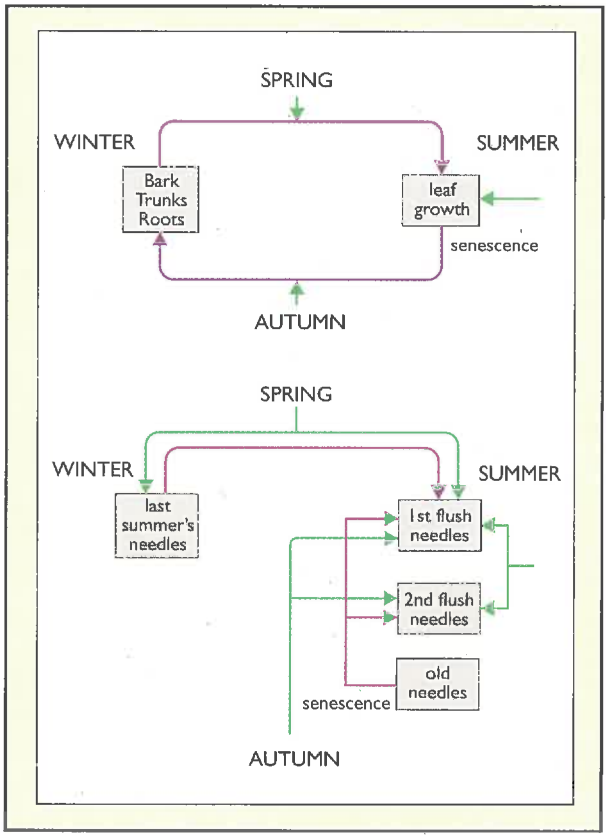

Figure 4. The seasonal pattern of nitrogen storage and remobilisation in deciduous trees (top) and evergreen conifers (bottom). The main fluxes of nitrogen are shown as remobilisation (——) and uptake from the soil (——).

the sustainable management of fruit orchards. With Agriculture and Agri-Food Canada (Pacific Agricultural Research Centre) we have refined the timing of nitrogen application to irrigated and fertilised apple orchards (Neilsen *et al.*, 1997), determining that nitrogen applied early in the season during spur leaf growth was not utilised by trees for growth. Collaboration with the University of Bologna has enabled us to study the use of foliar sprays of urea as a means of fertilising nectarine trees post-harvest to augment their internal cycling of nitrogen (Tagliavini *et al.*, in press). We have also studied methods for fertilising pear trees (Tagliavini *et al.*, 1997).

Many studies have shown that nitrogen and water supplies interact in their effects upon photosynthesis and growth (e.g., Radin and Ackerson, 1981; Ghashghaie and Saugier, 1989). In contrast few studies have examined the interactive effects of nitrogen and water supply on respiration (Dickmann *et al.*, 1992) and whole plant carbon allocation (e.g., Liu and Dickmann, 1996). Such studies are important for relating short-term gas exchange measurements to longer-term plant growth responses (McCree, 1986). We have quantified the effects of varying nitrogen concentration in the irrigation or changing the frequency of irrigation on carbon allocation in young poplar (Ibrahim *et al.*, 1997). Results from this initial study have been used to manipulate the nitrogen and water supplies to trees so as to grow them with a near-constant but contrasting internal nitrogen concentration (Ibrahim *et al.*, submitted). This enabled the effect of drought stress to be determined in trees, with similar nitrogen status, and study of nitrogen stress in trees with a corresponding leaf water potential.

A great deal of attention has focused on the sustainable management of forests following the publication of Agenda 21 from the Rio Summit (UNCED, 1992). There is, however, a lack of definition for the meaning of sustainability in practical terms (Heinen, 1994). According to Nambiar (1996) 'questions concerning management strategies for sustainable forestry are global in scope, but the genesis and application of practices for achieving this are local and based fundamentally on the soil'. There is now an urgent need to define and develop indicators of sustainable forest management that can be applied at a local level and at reasonable cost (Proe, 1997).

One area of particular concern is the long-term impacts of harvesting (Maini, 1992), particularly the increased removal of nutrients associated with whole-tree harvesting (Kimmins, 1985; Hendrickson *et al.*, 1989). Computer simulation modelling has suggested that the use of whole-tree harvesting may lead to site degradation through the accelerated removal of nutrients (e.g., Proe, 1986; Rolff, 1988) although this aspect has been proposed as a measure to alleviate high levels of nitrogen deposition in Scandinavia (Lundborg, 1997). Empirical evidence to support predictions from modelling is rare and that which does exist is equivocal. Results have shown whole-tree harvesting has decreased subsequent tree growth on some sites (Proe *et al.* 1996) and increased regrowth on others (Hendrickson *et al.*, 1989). Short- and long-term effects have also been shown to differ, making interpretation of results particularly difficult (Lundkvist, 1988).

The ability to predict the effects of whole-tree harvesting at a site-specific level requires a detailed understanding of the processes by which harvesting may affect long-term site productivity (Proe *et al.*, 1994) (Figure 5). We have shown that whole-tree harvesting of Sitka spruce on less fertile sites in Kielder Forest, Northumberland (UK) can result in substantial growth reductions for at least ten years following replanting with a second rotation (Proe and Dutch, 1994; Proe *et al.*, 1996) (Figure 6). The reasons for this are unclear although it has been suggested that changes in microclimate and weed competition may be important soon after replanting and that nutrient supply may become important several years later (Proe and Dutch, 1994; Proe *et al.*, 1994; Proe, Dutch, Pyatt and Kimmins, in press). We have already demonstrated the importance that can be associated with the retention of coarse branch material in addition to the nutrient rich finer branches and foliage (Proe, Craig, Dutch and Griffiths, submitted). Our results suggest that delayed replanting (a common practice) may induce nutrient imbalances on sites prone to potassium deficiency due to the rapid loss of potassium from decomposing harvest residues. In addition, the delayed removal of harvest residues (following needle-cast) may partially mitigate any detrimental effect associated with whole-tree harvesting although the coarse branches may represent an equally important component of the residues. However, their influence may not be apparent for several years.

Future Developments

Following the recent appointment of Dr Eric Paterson to work on root physiology in our Soil-Plant-Animal Interactions Integrated Programme (IPU36), our research on grass ecophysiology will develop to consider the impact of management on rhizosphere carbon flow. Study of the impacts of nitrogen supply and defoliation on carbon loss from roots will link to work on microbial diversity in the rhisosphere in the Soil-Plant-Animal Interactions Integrated Programme (IPU36). Our collaborative links with INRA, developed under the auspices of the INRA-MLURI Twinning Agreement will be developed to consider joint projects studying resource acquisition by defoliated grasses in relation to root and shoot growth, considering spatial arrangements of root growth in relation to nutrient availability. Because dissolved organic nitrogen (DON) is the most abundant form of

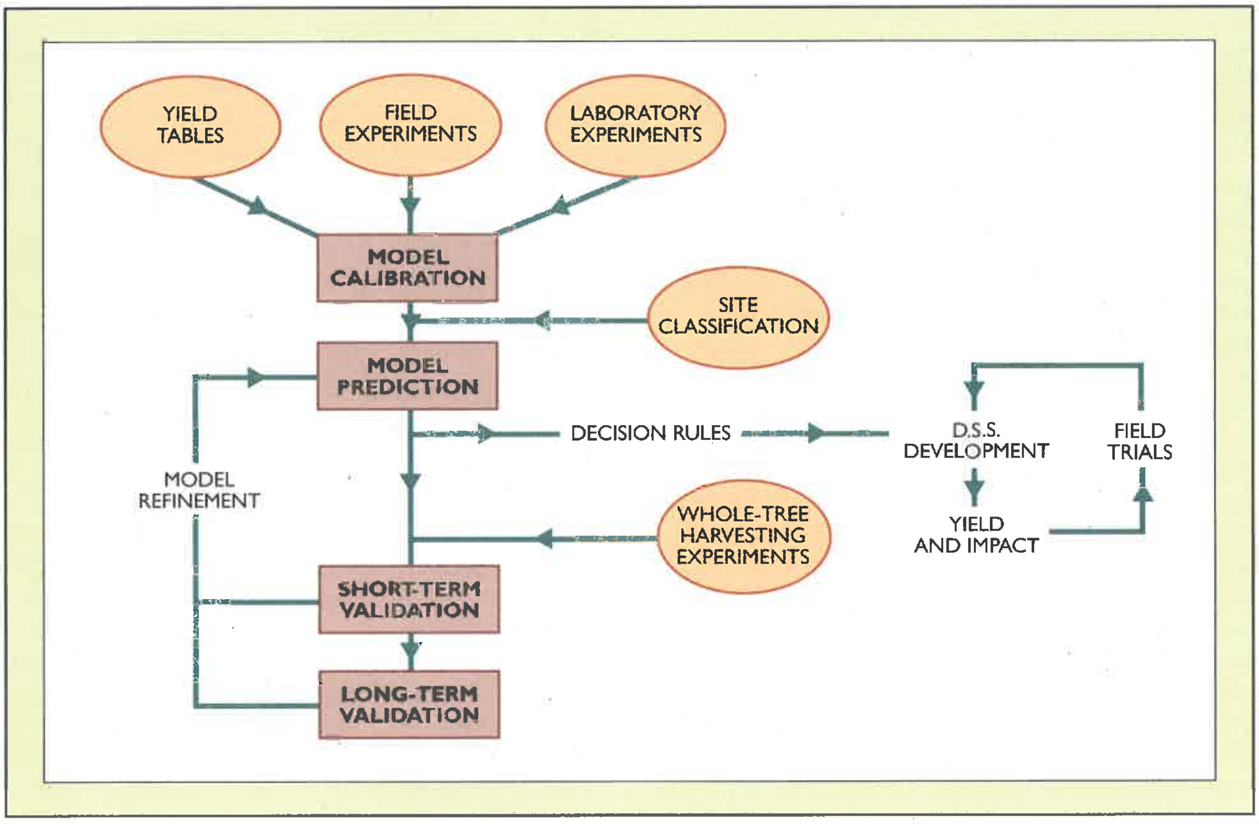

Figure 5. Strategies to develop whole-tree harvesting guidelines in Great Britain.

nitrogen recovered in soil solutions from upland organic soils we will also study amino acid uptake and use by grasses. This research will link closely to studies of the processes regulating nitrogen cycling in relation to the chemistry of DON in pasture soils in the Soil-Plant-Animal Interactions Integrated Programme (IPU36).

Research on tree ecophysiology will utilise xylem sap flow measurements in conjunction with amino acid signatures to quantify the amount of nitrogen remobilised during spring growth. This approach will be tested in field experiments using ^{15}N techniques to achieve an independent quantification of remobilisation. Once validated, amino acid signatures from xylem saps will be used to assess the impact of management on nitrogen storage by trees in a range of ecosystems, in order to develop sustainable management strategies. We will also study whole-tree assimilate partitioning to consider interactions between carbon and nutrient allocation in pine trees using a range of stable isotopes (^{15}N, ^{41}K and ^{26}Mg). Our research to develop Decision Support Tools for determining site suitability for whole-tree harvesting will also continue. A model of tree growth and ecosystem nutrient dynamics (FORECAST) is being calibrated at present. This model will be used to predict the effects of whole-tree harvesting on a range of site types, classified by soil nutrient status and results compared with output from a range of field experiments that are already established.

Relevance to End Users

Ecophysiology of grasses

Management of hill and upland pastures is becoming more extensive, with fewer inputs of fertiliser and grasslands supporting fewer grazing animals. Our strategic research, coupled with that in the Natural Heritage Management - Vegetation Dynamics Programme (PU27), is contributing to the development of strategies for the sustainable management of hill and upland pastures. Understanding the processes by which grasses acquire and use nutrients for growth, and compete for limited nutrient resources from heterogeneous soils is important for managing vegetation in low input systems. The response of grasses to defoliation is also very important in determining their competitive ability. The output of our research, therefore, will be of use to land managers and policy makers alike.

Ecophysiology of trees

An understanding of the relationships between nutrient supply, uptake and internal cycling in relation to tree growth is fundamental to the sustainable management of forest, woodlands, and orchards. The processes by which trees adjust to canopy perturbations are poorly understood and many of the models of tree growth are highly empirical. The knowledge gained from our research will improve our ability to predict the consequences for trees of management inputs (such as thinning or pruning) or

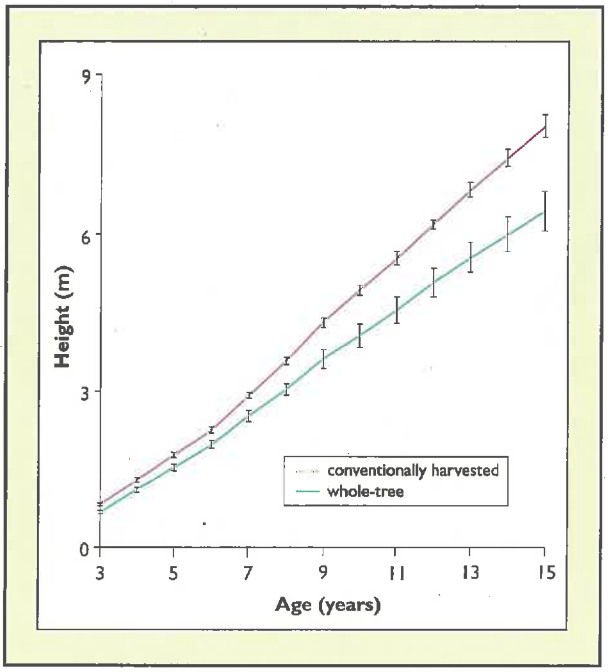

Figure 6. Effect of whole-tree harvesting on second rotation growth of Sitka spruce in Kielder Forest.

damage caused by defoliation or browsing. The extent to which fertilisers can be used to counteract such perturbations is largely unknown and our research will contribute in the longer-term to developments in this area of forest management.

Our studies of the impact of the timing of nitrogen fertilisation on the internal cycling of nitrogen in orchard trees has already contributed to the development of more sustainable orchard management protocols. However, this research is also applicable to trees grown in a wide range of land use systems and so will be of use by foresters, land managers and policy makers.

The forest industry is coming under increasing pressure, from the market place, to demonstrate that the products from forests have come from a sustainably managed resource. Harvesting practices can have a major effect upon forest soils and their surrounding environment. Forest managers require tools that will enable them to ensure that their forests are being managed in accord with the principles of sustainable development as stated at Rio Summit and developed thereafter. Our research on whole-tree harvesting will allow sites to be classified according to the likely risks and the potential effectiveness of ameliorative measures available to the forest manager.

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The research undertaken focuses on issues that are important for the sustainable management of all hill and upland areas of the UK.

Natural Heritage Management - Vegetation Dynamics

The marginal lands of Scotland are subject to many land use demands, including agricultural output, game management, recreation, wildlife and landscape conservation. These demands most often centre on the utilisation of the vegetation by combinations of wild (primarily deer) and domestic herbivores (sheep and cows), and how this utilisation interacts with edaphic conditions and other management practices. As in other areas of the world where agriculture is marginal, these multiple demands require balanced integration if both rural and ecological sustainability is to be achieved. However, it is in these marginal lands, rather than in more intensively managed areas, that the greatest changes as a result of altered agricultural support, new conservation strategies, increased recreational pressures and climate change are most likely to occur.

The marginal lands of Scotland contain a number of important habitats recognised by both the EC Habitats Directive (European Commission, 1992) and the UK Steering Group on Biodiversity (UK Biodiversity Steering Group, 1995), namely native pine woodland, montane habitats, upland heathland and blanket bog. The work in the Vegetation Dynamics Programme (PU27) provides objective information to aid the management and integration of land uses in marginal land areas. It provides predictive methods to inform the decision making process. The aim of the research is to maximise the value of biodiversity and landscape within the context of a sustainable rangeland farming system. Our research is essential to the fulfilment of the goals set out within Britain's environmental strategy, This Common Inheritance (Department of the Environment, 1990).

Within both the theme Sustainable Management of Marginal Lands and the remit of the Institute as a whole, this programme provides predictions on how different management choices will affect the vegetation of these marginal areas. It thus provides part of the strategic framework for the research of other programmes such as those concerned with the foraging behaviour and productivity of grazing animals, as well as contributing vital information to research within the theme of Sustainable Integrated Land Use Options.

Strategic Objectives

Briefly, the aim of the research of the Vegetation Dynamics Programme is to understand and predict the spatio-temporal dynamics of vegetation to changing demands imposed by herbivore grazing or other forms of land management. This is achieved by investigation of the responses of ecological processes to experimental manipulations of management and by the construction of models using this information to predict vegetation change at both the large and small scale. The strategic aims of the programme are as follows:

- To investigate the spatial processes and species interactions in agricultural grasslands.
- To understand the spatial and temporal dynamics of heathland communities as affected by burning and different grazing pressures.
- To investigate the effects of browsing and grazing on the dynamics of native tree regeneration in upland communities.
- To develop predictive models of these processes to provide simulations of long-term changes in management.
- To investigate the effects of soil type and climate on vegetation dynamics.

The research undertaken focuses on issues that are important for the sustainable management of all hill and upland areas of the UK. The programme links closely to the Land Use Options for Plants Programme (PU26) with the work on grasslands, tree physiology and the modelling of plant responses to defoliation. It also links closely to the Natural Heritage Management: - Herbivore Foraging (PU28) and the Land Use Options for Animals Programmes (PU29), as the impact of defoliation by herbivores is important in determining vegetation change. The pattern and productivity of vegetation in turn influences the behaviour and productivity of grazing animals. A number of staff within this group use their expertise as part of the Integrated Programme Unit, Long-term Measurement and Management of Change (IPU37) and the modelling work has become a vital part of a number of decision support systems in the Integrated Programme Unit, Development of Decision Support Systems (IPU38).

The specific objectives of the research have been:

- To investigate competition between grass species at a range of scales and under different defoliation regimes.
- To investigate the establishment and development of species aggregations in grasslands, in particular white clover, and the effect of this spatial aggregation on competition and the spread of species.
- To further elucidate the changes that occur within grassland swards under reduced stocking rates and fertiliser inputs.
- To investigate the effects of burning and grazing on the dynamics of a range of dry and wet heather-dominated communities.
- To establish appropriate stocking rates to allow for the rehabilitation of degraded wet heather moor.
- To analyse the effects of grazing by different herbivores on the behaviour of grass-heather interfaces and the processes of heathland fragmentation.
- To investigate the effects of grazing on the spread and regeneration of native woodland.
- To analyse the effects of browsing on the chemical and physical responses of regenerating tree saplings.
- To develop predictive, computer-based models of vegetation dynamics, integrating information on soils, vegetation types, climate, grazing species and the intensity of grazing.

As can be seen from these objectives, the work in the Vegetation Dynamics Programme is focused in four main areas. Three of these deal with the dynamics of different vegetation types viz. grassland, heather moorland and woodland, and the fourth deals with the modelling of vegetation change. The grassland orientated work centres on the effects of management on species composition. As a consequence of current and probable future changes in agricultural support and farming practice, much of the research carried out now deals with the question 'what happens to previously intensively managed grasslands when they are managed extensively?' Work on heather-dominated communities is geared to understanding the interactions between the age of heather, the burning regime and intensity of herbivore grazing on their regeneration and long-term sustainability. It is also concerned with investigating the reasons for heathland fragmentation. The third experimental area covers the ecology of woodland regeneration. Much concern has been expressed over the prevention of woodland regeneration by browsing animals, and the work within the programme is focused specifically on understanding the response of tree saplings to browsing damage.

The modelling work within the programme has two main objectives. Firstly, to integrate the information gathered in both current and past experimental investigations as a means of extrapolating to different scenarios and, second, to generate hypotheses for testing in the field. The models have also been adopted for use in decision support systems as a mechanism for transferring the results of research in the programme to practitioners in the field.

Achievements

Important achievements from last 12 months have been;

- Innovative research with the Scottish Crop Research Institute has shown the potential for using naturally occurring stable isotopes to elucidate the food web structure and energy flows in temperate grasslands (Marriott *et al.*, in press).

- Within a grassland undergoing extensification, we have shown that the colonisation of artificially created gaps was primarily by vegetative spread of the surrounding plants, and that seedling regeneration was of relative unimportance in these previously intensively managed systems (Marriott, *et al.*, 1997).

- The foraging behaviour of grazing red deer and sheep have been shown to be differentially affected by the size and distribution of grass patches within heather dominated communities, with sheep being more strongly affected by vegetation pattern than red deer. These effects on foraging behaviour in turn caused significant spatial variation on the utilisation of vegetation and the pattern of heather fragmentation.

- Regeneration of wet heathland vegetation has been shown to be critically dependent on the age of the heather before burning. Heather burnt in the late-mature phase of growth regenerated slower than heather that was in the late-building/mature phase, and was more severely affected by grazing.

- We have demonstrated that degraded heather stands can be rehabilitated without the need for the exclusion of all grazing animals, and that the absence of summer grazing in fact had a deleterious effect on regeneration.

- A vegetation dynamics model has been developed which has been included in both the HILLDEER and HILLPLAN grazing system decision support systems.

Current Research

The effect of extensification of grasslands

Three long-term experiments on grassland extensification were set up at different sites in 1991 to establish the consequences of reducing grazing intensity and fertiliser inputs on intensively managed sown pastures. The three experimental sites are situated on different soil types to represent the range of variation in Scotland, so that any conclusions drawn should be more applicable than conclusions drawn from a single site (Institute of Grassland & Environmental Research, 1996). However, the general effects of treatment have been similar at all sites (Marriott & Gordon, in press). Changes in ungrazed swards were dramatic after two years, with the almost complete elimination of the sown species, though the succession at the three sites resulted in different dominant species. Extensively grazed swards changed more slowly; fertilised swards maintained a high cover of *Lolium perenne* (ryegrass) as did unfertilised, autumn hard grazed swards (grass height maintained at 4cm). Clover (*Trifolium repens*) was favoured in the swards hard grazed (maintained at 4cm) in the summer. However, after six years changes in species composition are still occurring.

In addition to the main experiment, a wide range of work has been carried out using this facility (Figure 1). As a consequence of this and the continuing vegetation changes seen in the experiment, the treatments are planned to continue for a further 6 years.

One of these interesting studies has affected our current understanding of the mechanism of vegetation dynamics. Soil physical characteristics were studied in the different treatments, as were their effects of species interactions. Root and shoot growth were both reduced under moderate and severe mechanical impedance, but different species were affected in different degrees. Thus trampling or other means of soil compaction could be important in affecting competitive interactions in vegetation (Cook *et al.*, 1996, 1997). In collaboration with the Scottish Crop Research Institute, we demonstrated for the first time that the measurement of stable isotopes of carbon (^{13}C) and nitrogen (^{15}N) in grasslands communities could reveal how food webs and energy flows link within these systems (Marriott *et al.*, 1997).

- Soil compaction can alter the competitive interactions between species.
- Gap colonisation in sown pastures is dominated by vegetative spread of species surrounding the disturbance.
- Growth of individual rye grass plants is improved if their neighbours belong to other species.
- White clover growth rate has been shown to be dependent on where the growing point is situated in a patch and the size of the patch.
- Trophic patterns in ^{13}C and ^{15}N distribution could be measured by seasonal changes.
- The Sourhope study site has been used as part of the MICRONET study.

Figure 1. Outputs from the extensification experiments.

The mechanisms of heathland fragmentation

Fragmentation of heather and conversion to grass under heavy grazing is a widespread phenomenon in the British uplands, attributed in particular to the effects of sheep and red deer (Miles, 1988; Tudor & Mackay, 1995; Staines, Balharry & Welch, 1995; Hester, Miller & Towers, 1996), but little is known about the processes by which fragmentation occurs under grazing by the different herbivores. Most grazing-related vegetation change is thought to occur at the grass:heather interface (e.g., Grant *et al.*, 1978; Clarke *et al.*, 1995; Hester *et al.*, 1996), which means that the spatial distribution of the vegetation, as well as its composition, will be an important determinant of both the rate and the pattern of fragmentation under grazing. An experiment has been initiated to examine the patterns of impact by sheep and red deer grazing separately or together within areas of fragmenting heather.

Heather utilisation by both species declined rapidly with distance from the grass patch (Figure 2), with both herbivores grazing similar amounts of heather except in autumn where heather utilisation by deer was greater than that by sheep. Differential patterns of use of grass patches by sheep and red deer resulted in greater heather utilisation around larger grass patches by red deer, but similar heather utilisation by sheep around grass patches of all sizes.

Both species grazed less heather at the downhill edge of grass patches than uphill or across the slope (Figure 3). Grazing impacts were greatest uphill of grass patches for both herbivores but their patterns of impact around different grass patches diverged when a range of grass patch sizes were present. Patterns of impact as a result of trampling damage differed from those due to grazing, with damage concentrated at downhill edges of patches and paths, with corresponding

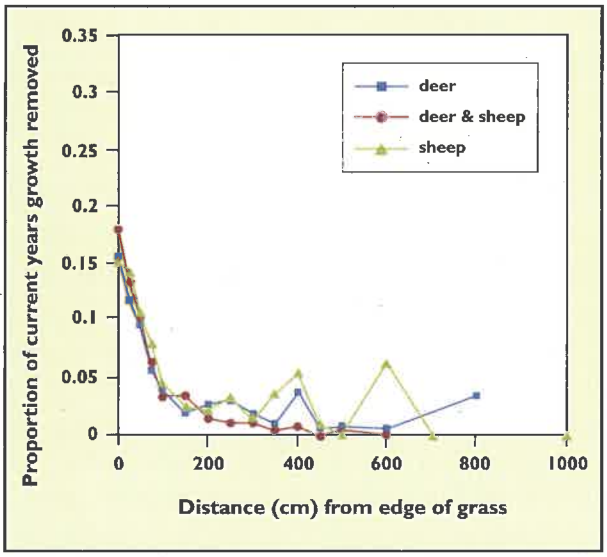

*Figure 2. Heather (*Calluna vulgaris*) utilisation by sheep, red deer and a sheep/deer mixture with distance from edge of grass patch, 1992.*

increases in cover of species such as *Vaccinium myrtillus* where the heather had declined. It appeared that at lower herbivore densities trampling may have more important impacts on the heather than grazing. As herbivore densities increase, the relative importance of grazing will increase, thus changing the patterns of impact on the vegetation. Sheep appeared to be much more affected by the pattern of heather fragmentation than red deer and their habitat use was more closely linked to paths and grass patches as foci. This contrasts with the more even habitat use by red deer. Such differences have important implications for the management of upland grazings; sheep grazing at the same intensity as deer will result in faster rates of heather fragmentation.

This work links both basic and applied research; tests of hypotheses concerning herbivore foraging behaviour are linked with the provision of information needed to understand processes currently occurring within Scotland's countryside. Many studies have shown how grazing animals select their diet and the effect of this selection on the vegetation, however this work shows for the first time that the scale and spatial arrangement of habitat patches has a crucial influence on vegetation dynamics.

The sustainable management of heather

The sustainable management of the diverse range of heather moorlands in Scotland is vital in maintaining both the landscape character and the biodiversity associated with them (Ratcliffe & Thompson, 1988). In particular, there is the potential for large-scale degradation of these habitats following inappropriate burning regimes and over stocking during critical periods of heather regeneration.

Long-term experiments carried out by MLURI have shown that the age of heather before burning is critical to the rate of subsequent stand regeneration. Regeneration in wet heathlands was better in stands of late building/mature heather (15 years old) than in stands of late-mature phase (30 years old) heather. Under year-round, moderate stocking densities of sheep, heather regeneration was reduced to a greater extent in the older heather stands. In particular, the growth of *Molinia caerulea* (purple moor-grass) and *Carex nigra* (common sedge) was favoured.

As it is difficult to remove land from grazing entirely, both practically and economically, then management strategies must be developed to improve the success of heather regeneration in competition with other species after burning. One of these competitors, *Molinia*, is a deciduous grass, and it has been shown to be controlled by summer grazing in other situations (Grant *et al.*, 1996). To test this further, an experiment was set up in 1996 to investigate the effects of summer only grazing on heather regeneration. Grazing pressure was regulated by monitoring grass height and adjusting stocking densities to maintain two set heights. Even after one year's growth, it is evident that heather regenerates better without grazing but may later suffer from competition with the *Molinia* (Figure 4). Under high grazing pressures there was almost no heather or

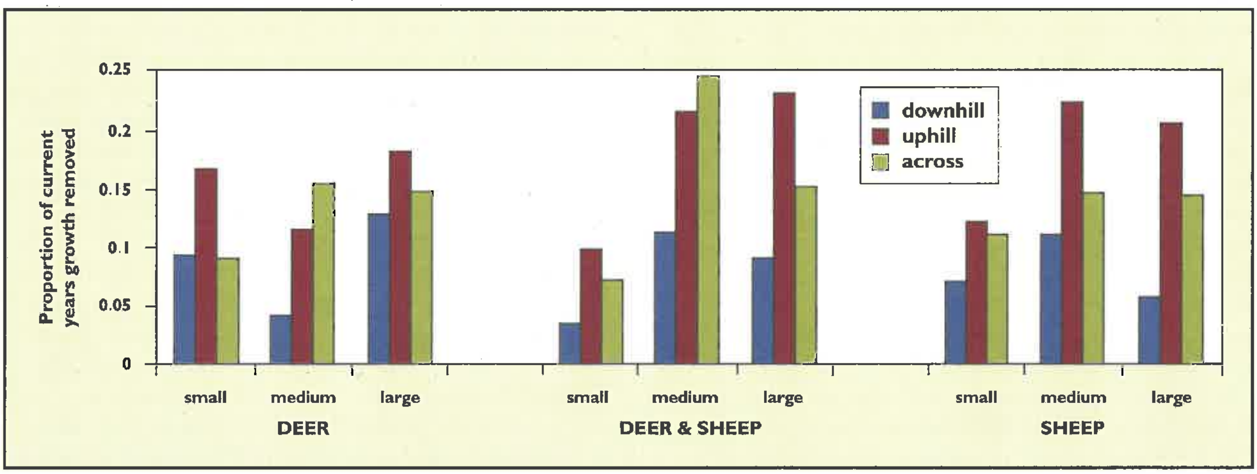

*Figure 3. Downhill, uphill and across slope heather (*Calluna vulgaris*) utilisation by sheep, red deer and a sheep/deer mixture within 50 cm of small, medium and large sized grass patches, 1992.*

Molinia growth, but under low grazing pressures there was heather regeneration without expansion of *Molinia*. These results and the results of current experiments will be critical in revising the Environmentally Sensitive Areas management prescriptions.

Modelling vegetation change in the uplands

A vegetation dynamics model has been developed which has been included in both the HILLDEER and HILLPLAN grazing system decision support systems. The model has the following features:

- It is generic, allowing new species and different grazing systems to be incorporated, and can be used for theoretical as well as practical purposes.
- It uses easily measured or easy to abstract information for the simulations.
- It is particularly suited for simulating areas where grazing is a major factor influencing the species composition of vegetation, as the algorithms used are quantitative and can be directly linked into grazing system models by using the predicted off-takes.
- It translates changes in composition to changes in areas of community type, which is particularly important in the communication of results to users.
- It is fast and hence can be used interactively. Further developments will increase the impact of spatial variables in controlling the direction and rate of predicted vegetation change.

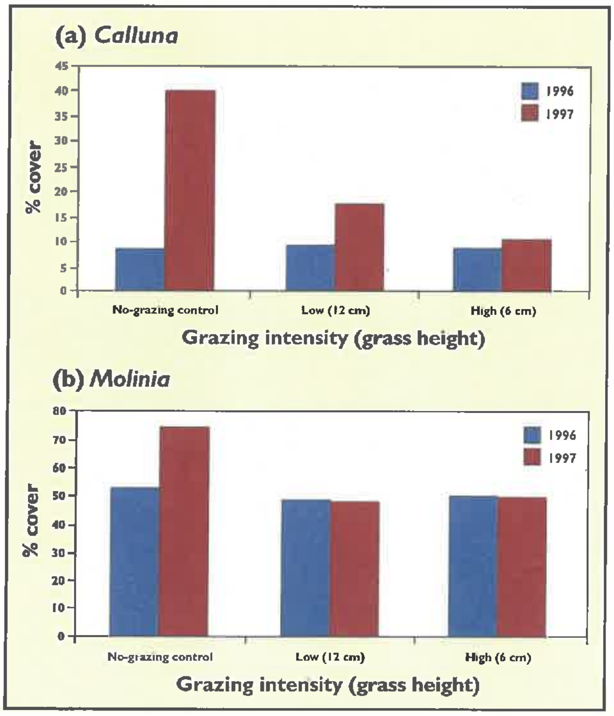

Figure 4. Change in cover (%) of (a) Calluna vulgaris *and (b)* Molinia caerulea *under three different grazing regimes at Redesdale, from 1996 to 1997.*

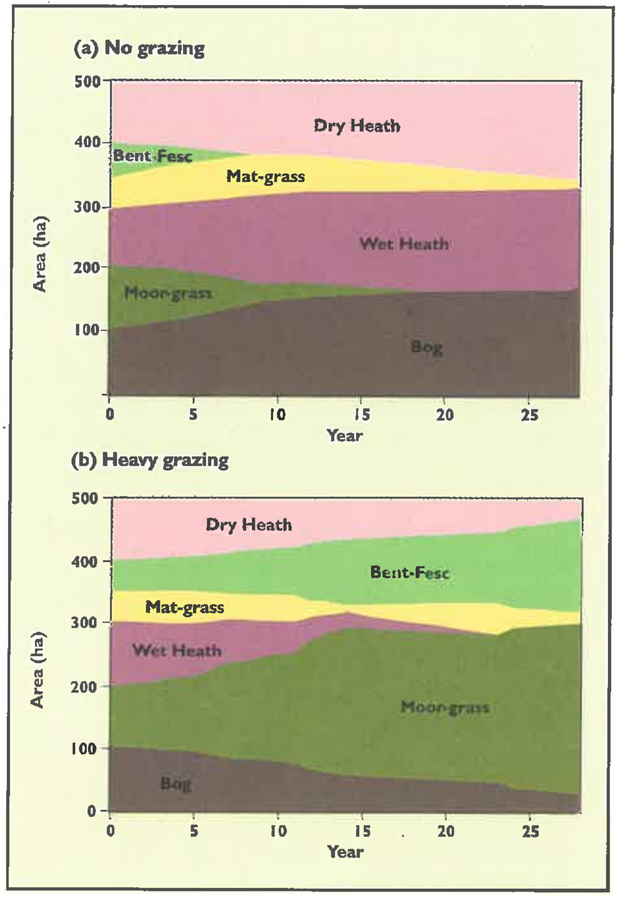

Figure 5. Change in areal extent of six upland vegetation types under two simulated management scenarios (a) no grazing, (b) heavy grazing. Moor grass Molinia caerulea; *Mat-grass* Nardus stricta; *Bent-Fesc* Agrostis capillaris-Festuca ovina.

It differs from the approach of other models in that it is does not rely on rule bases derived from large datasets (Sanderson & Rushton, 1995), nor is it restricted to certain communities (Hill, 1992; Pakeman, Hill & Marrs, 1995). Primarily it provides the opportunity for the grazing animals to drive vegetation change through their choice of forage, rather than in most models where the dynamics are allowed to occur only within the community of interest. Thus the whole grazing system can be covered in one simulation.

An example of the output from the model can be seen in Figure 5. The same range of hill communities was subjected to two different, simulated grazing treatments. The vegetation dynamics are presented clearly. Under no grazing there is a succession away from grass dominated communities to ones dominated by heather or to bog. The reverse is seen under heavy grazing – an increase in the area of bent-fescue communities at the expense of dry heath and *Molinia caerulea* dominated communities at the expense of wet heath and bog communities.

Future Developments

The broad aims of the programme will remain the need to understand and hence be able to predict the changes in vegetation as a result of changing land management or herbivore usage. Our approaches must take into account the reduction of stock numbers grazing indigenous vegetation, the effects of climate change, and the importance of soils in influencing successional processes. The latter will be aided by integration of our work with that carried out as part of the Integrated Programme Unit Soil-Plant-Animal Interactions (IPU36). Scientifically, we will continue to put greater emphasis on the need to understand the role of spatial scale in the processes being investigated, and hence a greater need for the integration of results and observation via computer based-models. The influence of pattern of the surrounding vegetation and the distribution of external seed sources which drive succession in tandem with allogenic processes will also be investigated. The programme will be focused:

- To investigate the mechanisms which result in the development of spatial aggregation in grasslands under different management regimes and how this pattern of aggregation affects, and in turn is affected by, herbivore grazing selection. This will provide predictions for the effects of extensification on grassland composition and productivity.
- To investigate the mechanisms and processes which determine how species diversity is maintained in grasslands and what role this diversity plays in ecosystem function.
- To further develop management strategies for the sustainable management of heathland communities and to understand the critical timing of events that lead to successful regeneration.
- To investigate the factors which control the regeneration and survival of tree seedlings and saplings in upland communities.
- To further develop models of vegetation dynamics to include the spatial spread of communities and species.

Relevance to End Users

The work within the programme is highly relevant to policy makers and land managers within and outside Scotland. The experimental programme which has focused on the effects of extensification on grasslands is providing high quality and a considerable breadth of information which provides the basis for managing the change from intensive to more extensive systems of production.

The current work on the rehabilitation and sustainable management of dry and wet heath communities will form an essential part of the management of many of these habitats as the conclusions are made available to the conservation agencies and other land managers. Experience in this field has led to consultancy work for Scottish Natural Heritage (SNH) and other organisations.

Increasing the area of native woodlands in Scotland is high in the priorities of many organisations. Work within our programme and with other programmes is providing essential information to understand how grazing controls the regeneration of these woodlands. Collaborative work with organisations such as the Royal Society for the Protection of Birds (RSPB) will further increase the capacity of MLURI to predict where woodland will regenerate, how fast it will spread and what type of woodland will develop under different grazing pressures.

Technology transfer is vital for increasing the value of the research done to the wider user community. Traditionally this has been through the production of reports and other publications, seminars and field visits. Though still essential, these approaches have been supplemented by the development of computer based decision support systems. The vegetation dynamics model developed within the programme forms an intrinsic part of two of these decision support systems (HILLPLAN and HILLDEER). These in turn enable the experience and knowledge gained by MLURI to be easily accessed and used by the people directly involved in decision making on land use issues. In addition we will use the skills and experience gained in understanding the dynamics of Scotland's vegetation to provide advice for the management of similar systems elsewhere in the world.

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Knowledge of the behaviour of herbivores is fundamental to our ability to provide objective guidance for the sustainable management of natural resources.

Natural Heritage Management - Herbivore Foraging

An understanding of the foraging behaviour of large mammalian herbivores is fundamental to the development of sustainable management of marginal lands. Large herbivores are major determinants of ecosystem function and dynamics in most terrestrial biomes. Through their grazing, trampling, defecation and urination they affect nutrient flows, vegetation community dynamics and the responses of associated fauna. In turn, system characteristics such as resource composition, productivity and distribution determine individual and population nutrition of the herbivore. Consequently, knowledge of the behaviour of herbivores is fundamental in order to determine the relationships between individual animal and population performance, their resources including vegetation communities and the natural heritage in its entirety. Only through the development of this understanding will we be able to provide objective guidance for the sustainable management of natural resources.

The research thereby assists in the development of policies outlined by the UK Government White Paper on Rural Sustainability (HMSO, 1995 a) and in the implementation of its agri-environment measures, the Countryside Premium Scheme (Anon. 1997) and Environmentally Sensitive Area Management protocols (Anon., 1987) and woodland grant schemes. The approach taken is to conduct research at a range of levels from individual to the ecosystem, highlighted in the recent Technology Foresight Report on Agriculture and the Environment (HMSO, 1995 b).

Strategic Objectives

The overall aim of the programme unit is to quantify relationships between aspects of the habitat and the foraging behaviour of domestic and wild herbivores in heterogeneous ecosystems, such as the natural and semi-natural vegetation, permanent pastures and other ecosystems of upland UK, Europe, Africa and Asia. We aim to increase our understanding of these relationships through the development and testing of herbivore foraging theory. The effects of the distribution of vegetation, its physical and chemical composition, the variations in microclimate and the social interactions of animals on foraging behaviour are being studied through a combination of broad scale data collation and analysis, experimentation and modelling. Technology transfer is being achieved through the development of foraging sub-models for incorporation in Decision Support Tools, which will predict the impacts of grazing by species such as sheep, cattle and red deer on vegetation dynamics, animal production and population dynamics.

The research within this Programme Unit (PU28) links with that in the Natural Heritage Management - Vegetation Dynamics Programme Unit (PU27) and provides concepts and quantitative information for the Land Use Options for Animals Programme Unit (PU29) which focuses on agricultural livestock systems. The research contributes to the development of decision support tools within the Development of Decision Support Tool Integrated Programme Unit (IPU38) by providing rules for incorporation into models of the processes involved in the interaction between herbivores and vegetation. This will facilitate the development of generic Decision Support Tools for grazing systems across a range of ecosystems.

Within these broad objectives, the strategy of the Natural Heritage Management - Herbivore Foraging Programme Unit has been to identify gaps in current knowledge and to attempt to fill them, predominantly through experimentation. There has been a continued need to develop techniques to measure diet selection, particularly for measuring the ingestion of browse species in wild large herbivores. This has also led to investigations of the role of secondary plant compounds found in browse species and how the development of conditioned food aversions may reduce the consumption of plant species containing secondary compounds.

Research has continued to develop an understanding of how large herbivores select a diet in relation to the dispersion of vegetation resources. We have well-recognised strengths in this area and have focused our research on the foraging behaviour and impacts, in relation to the consequences for biodiversity, of a range of species, including rabbits and red deer. New initiatives have been started to improve our understanding of decision-making by herbivores, namely the effects of climate and social behaviour and how these interact with the dispersal of vegetation resources to affect foraging behaviour. Theoretical approaches have also focused on the trade-offs that have to be made in the foraging behaviour of herbivores.

Specific Objectives

The specific objectives of the Natural Heritage Management - Herbivore Foraging Programme Unit have been:

- To refine methods for estimating diet composition and intake by free-ranging herbivores.
- To research the role of conditioned food aversions to secondary plant compounds in modifying the foraging behaviour of free-ranging ruminants.
- To ascertain the importance of the availability of shelter on the behaviour and energy status of large herbivores in the uplands.
- To quantify the role of the dispersion of resources on intake and patch selection of herbivores.
- To measure the effects of the social environment on foraging behaviour.
- To define foraging constraints and their influence on the response of wild and domestic herbivores to land use change.
- To determine the impact of grazing on biodiversity.
- To extend theoretical approaches to understand the decisions of herbivores foraging in heterogeneous systems.
- To assist in the development of the foraging components of Decision Support Tools.

Description of the Programme

Over the past 8 years the emphasis of the work has moved from the domestic ruminant, grazing sown pasture, to the interaction between domestic livestock and wildlife grazing extensive areas comprising mosaics of natural vegetation communities. The emphasis has been on the development of an understanding of the relationships between the availability and composition of resources, and diet selection and intake of large herbivores.

We have continued to link the development of herbivore foraging theory with experimental work in order to develop a mechanistic understanding of plant herbivore interactions at a range of scales. We believe that it is only through this level of understanding that we will be able develop predictive models of the consequences of grazing by large herbivores on the natural heritage and develop management systems for the sustainable utilisation of natural resources by both livestock and wildlife (Figure 1).

As a focus for our work we use a theoretical framework of the factors which affect the intake and diet selection of the free-ranging animal (Figure 2).

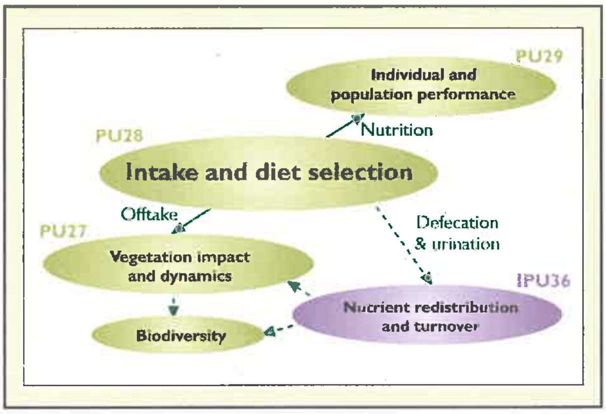

Figure 1. The central role of intake and diet selection of large mammalian herbivores in ecosystem function and the Macaulay Land Use Research Institute's Research programme.

The animal can be seen as having a set of drives to consume nutrients which are determined by its body size and its physiological state (e.g., stage of maturity, whether it is pregnant or lactating). In order to consume a diet which has an adequate level of nutrients to meet its requirements for maintenance, growth and reproduction, the animal is faced with a series of short-term tactical decisions about what diet to select, how long to search between bites and the resulting rate of food intake. In the longer term, strategic decisions concern the length of time to spend feeding, and where to feed given topographic influences on energy expenditure and distance travelled between foraging sites, water and shelter. This suite of decision-making processes is defined as the foraging strategy of the animal. The degree to which the animal is free to achieve its goals for nutrient intake will be related to the constraints imposed upon it, which are both internal and external to the animal itself. The animal's internal constraints include such factors as its morphology and physiology. For example, the breadth of the incisor arcade will affect the degree to which the animal can be selective for plant species or plant parts in a heterogeneous mosaic of plant material. Similarly, the adaptation of microbes in the rumen will determine the degree to which the animal can detoxify secondary metabolites in the plants it consumes. The external constraints include such factors as the structure and composition of the vegetation available, the social environment in which the animal lives and the distribution of shelter relative to forage resources. The degree of complexity of the decisions required will reflect the heterogeneity of the environment in which the animal is foraging. Animals whose resource represents simple monocultures, typical of sheep and cattle grazing temperate sown swards, have limited heterogeneity to deal with in everyday foraging choices. In contrast, on rangelands, comprising a mosaic of vegetation communities varying in their species diversity and structural heterogeneity the foraging animal has many more decisions to make. Our current programme of research has primarily focused on the development of an understanding of the role of those constraints which affect an animal's intake and diet selection. Our ultimate aim is to develop a holistic framework for predicting the spatial dispersion of communities of herbivore species in complex heterogeneous environments. This, in turn, will allow prediction of the spatial distribution of foraging pressure.

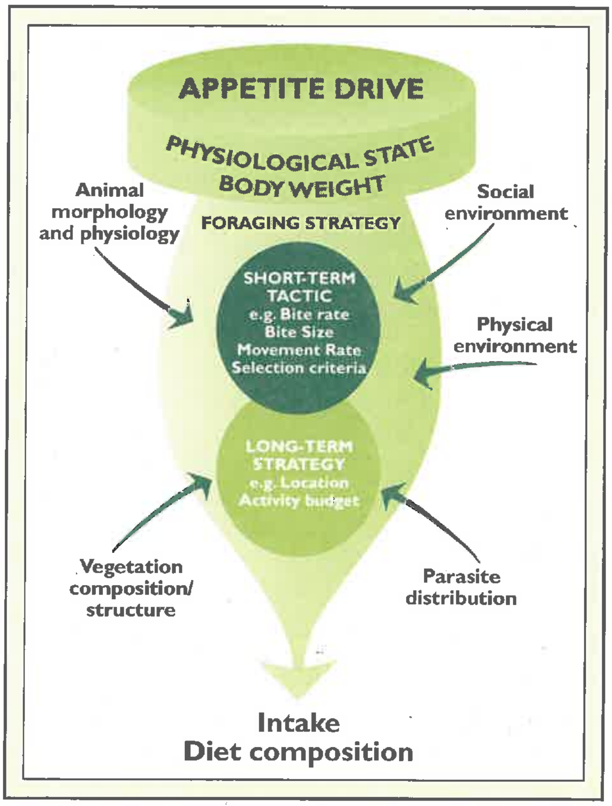

Figure 2. Schematic presentation of interactions between the tactical and strategic components of foraging strategy and external factors which influence animal intake and diet selection.

Achievements

- The functional response, that is the relationship between resource abundance and intake rate, has been shown to be the main determinant of foraging choice at a range of scales (Illius *et al.*, in press).
- Functional responses have been theoretically derived from fundamental properties of ungulate behaviour leading to an equation which describes the optimal diet choice of an ungulate including the effect of digestive rate constraints (Farnsworth and Illius, 1998).
- The amount of time available for foraging has been shown to be a key constraint to intake of grazing herbivores (Iason *et al.*, in press).
- The group has continued to identify and evaluate potential plant markers, including n-alkanes, to improve the accuracy and precision of methods for estimating diet composition for herbivores, Mayes *et al.*, 1995.
- Measurement on a range of vegetation communities has shown that variation in arthropod biodiversity was a product of the relative influence of grazing management and larger scale environmental variables (Dennis *et al.*, 1997).
- A computer-based Decision Support Tool (HILLDEER) has recently been completed which provides a means of estimating the consequences of red deer population size on vegetation utilisation and dynamics, individual red deer performance and population dynamics (Gordon and Hope, 1998).

Current Research

Theory development

Fundamental to an understanding of the relationship between the foraging herbivore and the resources upon which it feeds is the development of foraging theory (Stephens & Krebs, 1986). In a generalisation of the Ideal Free Distribution (Fretwell & Lucas, 1970) we have developed a theoretical understanding of the spatio-temporal systems which describe ungulate foraging when resources are dispersed unevenly within ecosystems. We have derived a more general equation than that attributed to Holling (1959), allowing ungulates to be included in the contingency model of optimal foraging (Farnsworth & Illius, 1996). This has enabled us to derive functional responses from fundamental properties of ungulate behaviour leading to an equation which describes the optimal diet choice of an ungulate including the effect of digestive rate constraints (Farnsworth & Illius, 1998). This has demonstrated that a mixed diet is a possible optimal selection in certain circumstances (breaking the conventional zero-one rule; Stephens & Krebs, 1986) and shown the dominance of digestion rate of forages in optimal foraging choices. In further theoretical developments, we have derived general equations describing the spatial behaviour of animals including social and cost-minimising behaviour. We have shown that the Ideal Free Distribution is a limiting special case of these relationships (Farnsworth & Beecham, 1997). The theory and relationships derived from the programme of research in this area have successfully been incorporated into the Decision Support Tools under development at MLURI (HILLDEER and HILLPLAN).

Technique development

In order to understand the impact of herbivore foraging on vegetation and animal productivity, there is a need for information on plant composition, nutritional quality and intake of diets of individuals and groups of animals (Hodgson & Illius, 1997). The development of techniques is an essential component of the research as this allows us to test hypotheses about the factors affecting the foraging strategy of free-ranging herbivores in extensive systems (Gordon, 1995). Here at MLURI, we are amongst the leaders in the development of techniques for use in grazing ecology research. Recently, progress has been made in the identification and evaluation of plant compounds, including n-alkanes and other hydrocarbons (Dove & Mayes, 1996), which can be used to improve the accuracy and precision of marker methods for estimating intake, digestibility and diet composition for wild and domestic herbivores (Mayes *et al.*, 1997). Isoalkanes and both odd- and even-chain alkanes have been found in certain grasses and a range of browse species, and their recovery in faeces has been determined. Long-chain fatty alcohols and plant sterols have been detected in herbivore faeces and studies to evaluate faecal recovery are in progress. Evaluation studies have been carried out in horses, pigs, fallow deer and rabbits. New methods for dosing even-chain alkanes have also been tested. A modification of the alkane method allowing intake and diet composition to be determined for grazing periods of less than 2 days has been developed and tested (Figure 3). Collaborative work with the Rowett Research Institute and CSIRO (Australia) to examine the potential combined use of faecal and urinary markers to characterise diet composition, dietary nutritive value and nutritional status of grazing ruminants has been initiated (Mayes *et al.*, 1995). In relation to this work, equipment for measuring and sampling urine output has been developed.

Toxins and diet selection in free-ranging ruminants

Free-ranging ruminant herbivores encounter a wide range of potentially toxic compounds in different species of plants (Cronin *et al.*, 1978). The behavioural mechanisms used by the animal to ascertain the toxic effects of these plants and then to avoid them are not well understood. One hypothesis, which is currently the subject of considerable research interest around the globe, is that herbivores develop conditioned food aversions to limit their consumption of toxic plants (Provenza, 1995). Research to date has focused on the use of unnatural toxic stimuli to develop and investigate aversions (e.g., Ortega-Reyes & Provenza, 1993). In our experiments with sheep and goats, we have adopted an experimental model that more closely reflects the forages encountered by free-ranging ruminants. We have extended previous work on conditioned food aversions, which have used artificial aversive stimuli, to demonstrate that ruminants can form aversions to more natural stimuli such as secondary compounds found in their food plants (Frutos *et al.*, 1998). Further work has shown that under free-ranging conditions, physiological adaptation to secondary compounds can modulate the strength of aversions developed and thus influence diet selection (Figure 4; Duncan *et al.*, in press, a).

Microclimate and diet selection in free-ranging ruminants

When foraging in rangelands, herbivores are faced with spatial and temporal variation in the dispersion of food resources. Range vegetation consists of a mosaic of discrete plant communities distributed across topographically heterogeneous landscapes. The costs of thermo-regulation in these environments can be high and the availability of shelter may help to reduce the costs (Staines, 1976). As a consequence, grazing behaviour is likely to be modified according to the degree of shelter as well as the quantity and quality of food available. Controlled experiments in which sheep were offered choices between sheltered and exposed foraging locations have provided insight into the relationship between motivation to seek shelter and

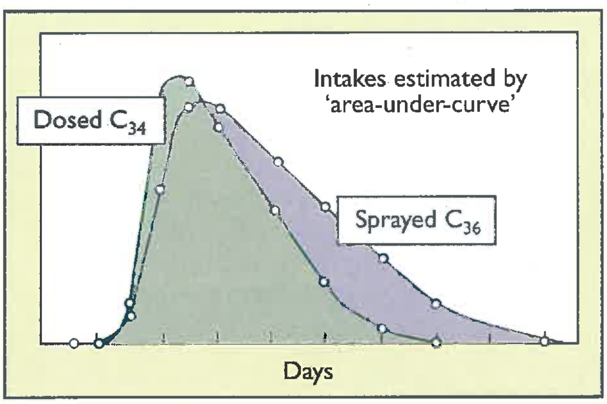

Figure 3. Short-term intakes can be estimated for free-ranging herbivores from the excretion patterns of n-alkanes following a pulse dose (Duncan et al., in press, b).

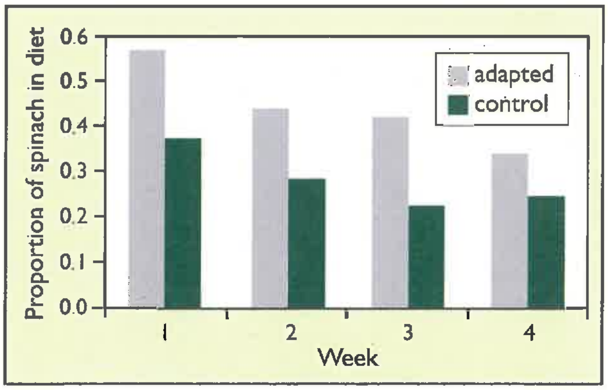

Figure 4. Rumen adaptation to oxalic acid increases selection for oxalic acid rich spinach feed in free-ranging goats (Duncan et al., 1996a).

the thermal physiology of sheep (Duncan et al., 1996b). Preliminary data suggest that the point at which foraging behaviour is modified by climatic conditions corresponds to the lower limit of the thermoneutral zone. Cold exposure minimisation has an overriding influence on foraging behaviour below the lower critical temperature (Figure 5; Duncan *et al.*, 1997). Extensive micro-climatic measurements have allowed an improved understanding of the relationship between foraging behaviour and the responses of sheep to weather.

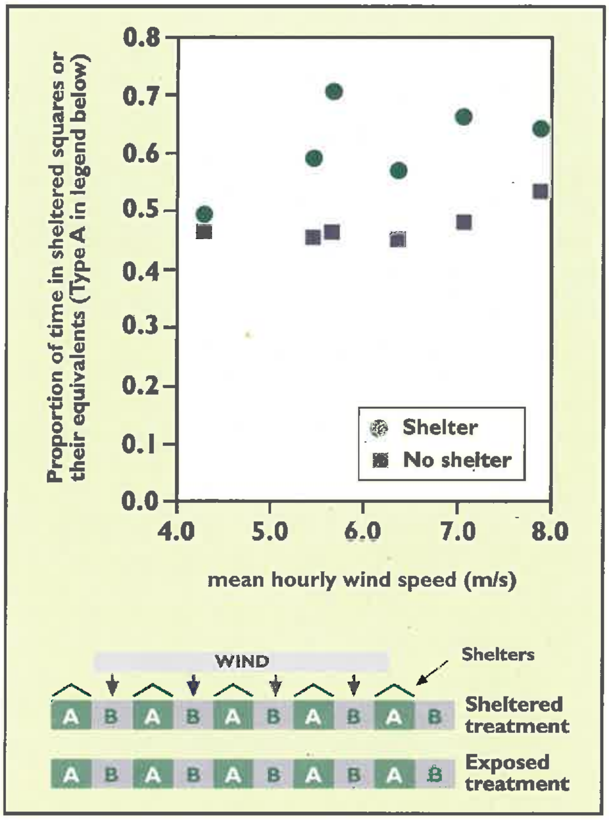

Figure 5. When given the opportunity sheep seek shelter more as wind speed increases (Duncan et al., 1997).

Resource distribution and diet selection in free-ranging ruminants

Resources are not evenly distributed in the environment, and the spatial dispersion of these resources has an influence on the ranging patterns of the herbivores and consequent effects on diet choice and intake (Gordon & Illius, 1993). Research in this area has been conducted at a range of scales, from bite via feeding stations to vegetation community (Gordon *et al.*, 1996b). At the level of the bite, an experiment using perennial ryegrass (*Lolium perenne*) and clover (*Trifolium repens*) demonstrated that the dispersion of these species at the feeding station scale did not influence the diet composition of sheep but did affect the rate at which they consumed herbage (Gordon & Illius 1997).

At the larger scale, research has focused on the effects of resource abundance within vegetation patches and the distribution of those patches on vegetation patch choice in free-ranging herbivores. The functional response, that is the relationship between resource abundance and intake rate, has been shown to be the main determinant of foraging choice at a range of scales. For example, the choice between two natural communities *Agrostis-Festuca* and *Nardus* by sheep is related to the difference in their intake rate, i.e. functional response (Gordon *et al.*, 1995). However, completed studies conducted in collaboration with the Institute of Terrestrial Ecology have shown that the dispersion of grass patches within heather moorland influenced vegetation community choice in sheep but not in red deer (Clarke *et al.*, 1995).

The response of herbivores to the distribution of parasite larvae in the environment is being investigated experimentally in collaboration with the Scottish Agricultural College. This research has shown that sheep are able to discriminate against patches of vegetation, which have been contaminated with faeces and show a significant avoidance of contaminated patches (Cooper *et al.*, 1994). This response is greater in individuals which are themselves carrying a parasite burden (Gordon *et al.*, 1996a). This is an exciting area of research as it demonstrates the animal's ability to alter its behaviour in a way that reduces the ingestion of disease forming organisms and how the internal milieu of the animal can affect foraging behaviour. It has important implications for the herbivore population biology.

Social behaviour and intake in free-ranging ruminants

Most mammalian herbivores live and feed in groups with some degree of social organisation. Although there have been studies on the dispersion of these groups and the interactions that take place between individuals (Arnold & Maller, 1985), there is a lack of information about how social behaviour may affect foraging strategy, particularly in heterogeneous ecosystems. By using an experimental design in which plot size is varied while animal numbers and sward conditions are kept the same, it has been possible to study the effects of stocking density on grazing behaviour, independently of the effects of herbage height or mass. With small groups of sheep, the distribution of animals at a range of stocking densities suggests that individuals may move fairly independently in small areas, where the distances between them are very similar to those that would be expected by chance. However, as plot area increases, mean inter-animal distance appears to reach a plateau. The amount of time spent in grazing activity has been found to increase as stocking density decreases and it may be that this is partly a reflection of the extra effort required by animals to keep within a certain distance of one another in larger areas. Some evidence was found from our experiments that particular relationships between individuals affect their grazing behaviour, but it appears that within small groups of non-productive female sheep there are no advantages conferred by social status, even if space is limited, when there is an adequate food supply. We are currently testing this hypothesis at higher stocking densities.

Resource availability and intake rate in free-ranging herbivores

Underlying the prediction of foraging choices in heterogeneous systems is knowledge of the relationship between resource availability and intake rate (functional response) (Fryxell & Lundberg, 1997). In principle, the observed intake and diet selection of foraging herbivores can be described as the outcome of the behaviour of the animal required to meet physiological drives for nutrients related to its physiological state, but constrained by aspects of the environment, internal and external to the animal (Figure 2). For example, we have shown that incisor breadth and structure is a primary determinant of the intake of grazing ruminants. In another piece of work we have addressed the hypothesis that the amount of time available for foraging is considered to be a key constraint to intake and diet selection by grazing herbivores. Both this constraint and the digestive ability of herbivores (Iason *et al.*, 1995; Gordon & Illius, 1996) have proved to be flexible and modifiable by behavioural and physiological adaptation (Figure 6). Our recent work has shown that experimental curtailment of available daily grazing time was counteracted by sheep increasing their rate of intake, but only when levels of food availability were high.

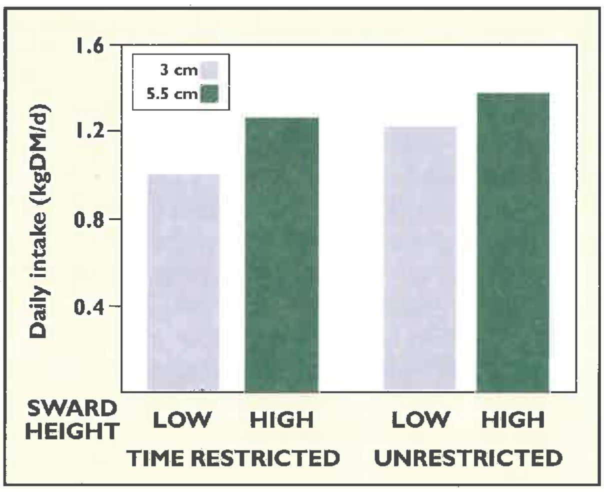

Figure 6. Sheep can compensate for a daily grazing time constraint, but only to a limited extent where herbage is in short supply (Iason et al., in press).

The relationship between rate of food intake and available plant biomass has been quantified for rabbits grazing grass swards. In conjunction with rabbit habitat selection experiments, it is concluded that potential food intake rate is a poor predictor of habitat selection in rabbits and that rabbit responses to changes in density of domestic herbivores are driven by the resultant structural changes to their habitat.

Grazing impact on biodiversity

Grazing has a major impact on the faunal biodiversity of natural ecosystems both directly through its impact on vegetation composition and structure and indirectly through the provision of food in the form of dung and carcasses (Gordon & Dennis, 1996). In our research in Scotland we have used sites of existing long term experiments which control grazing on some of the most ubiquitous natural vegetation communities in the UK hills and uplands to measure the effects of grazing pressure on invertebrate community structure and biodiversity. Stratified samples of insects and spiders were collected from experimental sites on three upland vegetation communities (*Nardus*, *Agrostis-Festuca* and *Festuca-Agrostis*), where grazing rates were continuously adjusted to maintain particular structural characteristics in the vegetation. Geostatistical procedures identified the spatial scale of interaction of different arthropod species from their distribution and abundance. The scale of variation of the arthropods was a product of the relative influence of grazing management and larger scale environmental variables (Figure 7; Dennis *et al.*, 1997). The method identified those species most sensitive to changes in grazing management from those with a wider distribution determined more by soil and topographic variations. Spiders and plant hoppers were sensitive to grazing rate and the distribution of grazing pressure within individual plots (Dennis *et al.*, in press). A prediction of the distribution of these partially sedentary species requires information on the foraging pattern of grazers, with

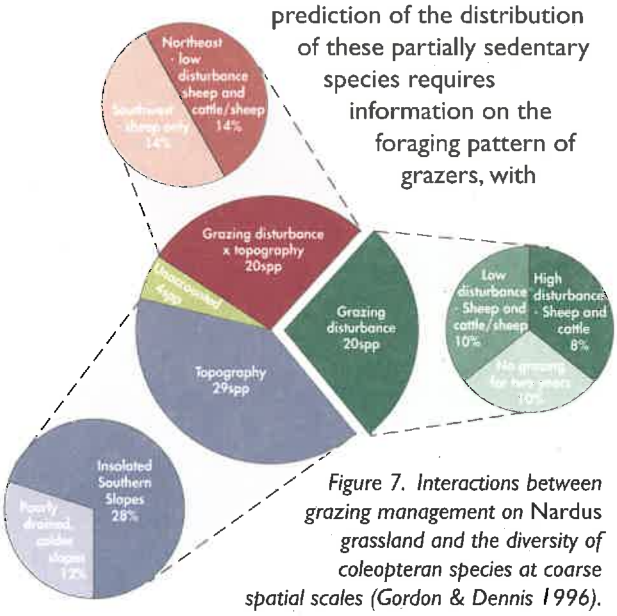

Figure 7. Interactions between grazing management on Nardus *grassland and the diversity of coleopteran species at coarse spatial scales (Gordon & Dennis 1996).*

reference both to resulting plant structure and disturbance by treading. Recent work has produced a database and grazing response model for application in biodiversity management in upland landscapes.

Decision Support Tools

In 1997, the Institute's research programme was restructured with the Natural Heritage Management - Herbivore Foraging Programme being included within the research theme Sustainable Management of Marginal Lands which also comprises the Natural Heritage Management - Vegetation Dynamics and Land Use Options for Animals Programme Units (PUs 27 & 29). The strong links between the three programmes will be maintained, so that a portfolio of integrated research projects can be developed to address this theme relevant both to the UK and abroad. In the future we will also continue to respond to the need to develop Decision Support Tools (IPU38) which allow the user to estimate the spatial distribution of herbivore impact. This will require us to generate and test hypotheses concerning the responses of herbivores to the spatial distribution of resources in the environment and also to the trade-offs involved in the choices of their distribution in the environment. It is also important to gain an understanding of how heterogeneous ecosystems involving grazing by herbivores function and research will be initiated at the appropriate time with colleagues researching the soil/plant/animal interface (IPU 36) (Figure 1).

Future Developments

The broad aim of the research within the Natural Heritage Management - Herbivore Foraging Programme Unit will continue to be the development of an understanding of factors that affect intake and diet choice of herbivores foraging across heterogeneous landscapes and the role of herbivores in driving and directing ecosystem processes. Emphasis will be on both domestic and wild species of herbivorous mammals, particularly ruminants. This will allow the programme to develop both nationally and internationally.

The emphasis of the programme of research over the next four years will be to develop our understanding of the factors influencing behavioural responses of free-ranging animals in complex ecosystems. To this end, a major theme underlying the majority of research within the Natural Heritage Management - Herbivore Foraging Programme will be that of understanding and quantifying trade-offs. It is hypothesised that animals foraging in heterogeneous ecosystems are constantly making decisions relating to the trade-off between the costs and benefits of particular actions and the various other options open to them. For example, an individual of a group-living species, such as rabbits, must make a decision about the trade-off between being close to companions and benefiting from their proximity but suffering from the competition from neighbours. On the other hand, it could be further away where the risk of potential predation is lower.

We will continue to use a mixture of approaches within the research programme as we believe that they provide synergy, which adds value to the portfolio of research. The approaches will include observational data collection from a wide range of sources in order to develop and test hypotheses concerning, for example, aspects of the relationship between resource abundance and red deer population performance. These studies will provide the ecological context for the development of specific controlled experiments to test specific aspects of foraging behaviour under more controlled conditions, both indoors and outdoors. In some cases the use of agricultural forages will provide us with model systems for testing the responses of herbivores to resource manipulation. The development of mathematically based theory also plays a central role within the programme by providing a more general framework into which to place the work and link it with other Programme Units within the research programme. With the expansion of our research into more extensive ecosystems we view the development of techniques, for example to measure diet composition and position and activity of large herbivores, as being of primary importance in our ability to test hypotheses in the field (Figure 8).

The impact of grazing management of biodiversity will be further developed by the production of models of the relationship between land use changes on

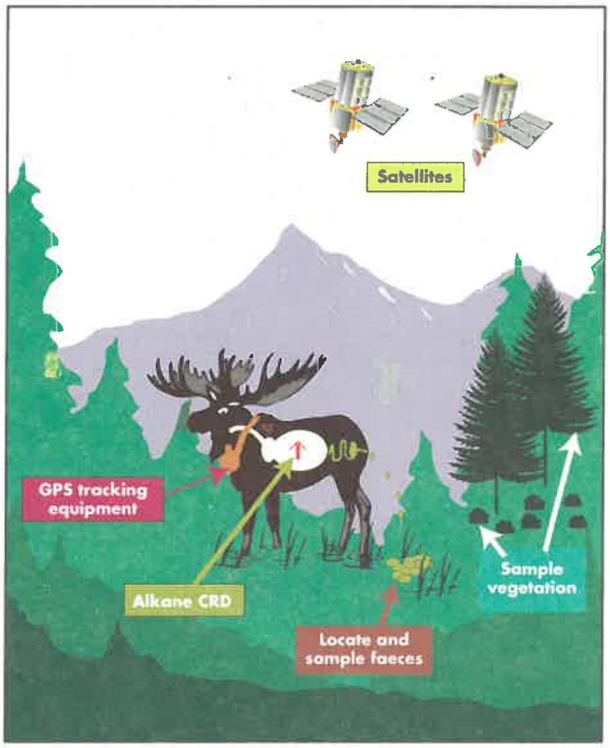

Figure 8. The programme continues to develop techniques for the measurement of movement patterns, herbage intake and diet selection in free-ranging ruminants.

invertebrate, bird and small mammal biodiversity. Such models will be linked with GIS databases in order to provide predictions at a scale most appropriate to link the management system with the animal response.

Relevance to End Users

One of the ultimate goals of the research within the Natural Heritage Management - Herbivore Foraging Programme Unit is to provide the theoretical framework, quantitative and qualitative rules and relationships, and parameterisation for the foraging aspects of Decisions Support Tools (e.g., Armstrong *et al.*, 1997). A computer-based Decision Support Tool (HILLDEER) has recently been completed which will provide a means of estimating the consequences of red deer population size on vegetation utilisation and dynamics, individual red deer performance and population dynamics (Gordon & Elston, 1997). HILLDEER consists of two major models, one for predicting vegetation production, red deer foraging and vegetation dynamics (the habitat and grazing model) and one for the prediction of red deer population dynamics. The foraging model synthesises current ecological theory, detailed experimental data and expert knowledge to provide a comprehensive computer-based programme relevant to red deer in the Scottish context. HILLDEER has been launched and will help deer managers such as the Association of Deer Management Groups, and regulatory bodies, such as the Deer Commission for Scotland, to assess the consequences of different culling regimes for deer population dynamics and hence allow improved management of habitats and the deer themselves. The Deer Commission for Scotland and the Association of Deer Management Groups are using the Decision Support Tool as part of a package of instruments to develop their deer management plans. HILLPLAN is a decision support tool designed for SOAEFD to predict the impact of grazing sheep and cattle on the dynamics of vegetation communities. A foraging submodel has been developed which predicts the vegetation patches grazed and the species within the vegetation patches. HILLPLAN is planned to assist in the implementation of Agri-Environmental schemes of the European Union at the farm scale in Scotland. These products demonstrate the application of the science conducted under the Natural Heritage Management - Herbivore Foraging Programme Unit (PU28).

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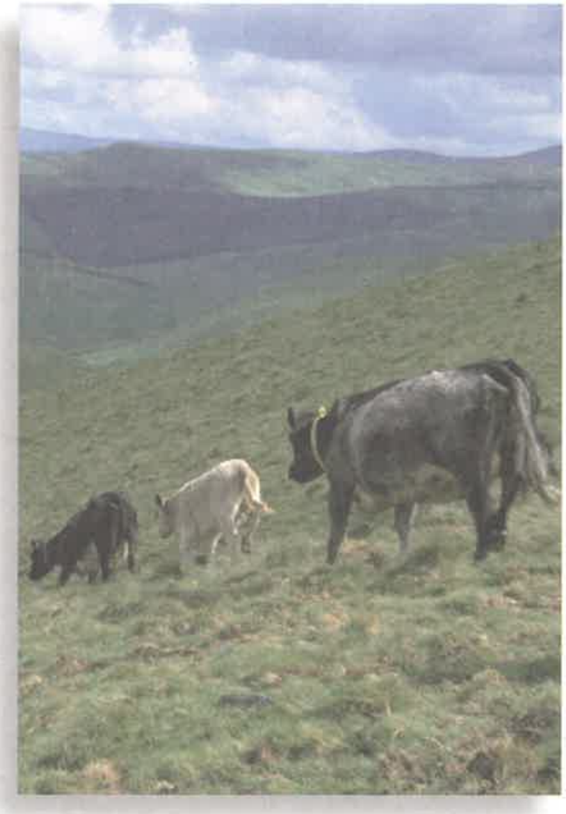

Ruminant animals are the principal means by which the world's rangelands and grasslands are managed and are crucial to the economic, social and environmental well-being of these areas.

Land Use Options for Animals

Ruminant animals play a major role in the use of much of the world's marginal land. They are the principal means by which the world's rangelands and grasslands are managed and exploited and are therefore crucial to the economic, social and environmental well-being of these areas. In Europe and the UK, as in other parts of the world, ruminant livestock forms the basis of the rural economy in many hill and upland areas. In Scotland, for example, 80% of the agricultural land in Scotland is not suitable for any form of agriculture, except that based on ruminants and ruminants account for 43% of agricultural output.

Within the EU there is concern about actual or potential surpluses of many agricultural commodities, especially meat which forms the basis of agricultural output from hill and upland resources. There is also concern about the impact of agricultural management on the environment, animal welfare and potential social consequences of policy change. In general, current policies encourage the extensification and diversification of land use systems involving ruminants and also encourage consideration of how they might be integrated with rural development initiatives outside agriculture.

Strategic Objectives

The overall aim of the research in the Land Use Options for Animals Programme (PU29) is to identify options for the sustainable use of marginal lands by ruminants. This is achieved by investigation of the biological properties of traditional and novel ruminant-based land use systems in relation to agricultural output and efficiency, environmental impacts, the welfare of the animals and taking account of the policy framework within which livestock systems operate. The successful development and management of these systems requires quantitative information about the underlying processes which govern their behaviour.

Animal fibre biology

The need to consider alternative systems of production on which to base diversified economic activity is addressed in research investigating the biology of fine fibre production from goats and sheep. Our research considers both the genetic and the environmental control of fibre production.

Animal behaviour and welfare

With increasing public concern about the welfare of farmed livestock, we aim to develop techniques for the assessment of the welfare status of animals in extensive management systems, to develop techniques for the assessment of motivation and to investigate factors influencing animals' behavioural needs.

Grazing systems

Since different ruminant species exhibit differences in their grazing behaviour and diet selection there is potentially scope for the better integration of different animal species into complementary grazing systems and we are investigating the principles of sequential and mixed grazing of livestock on a range of sown and semi-natural vegetation communities. We are also conducting research into the interaction between genotypes of beef cattle to different nutritional environments. The choice of appropriate genotypes, and in particular the influence of dairy breeding on suckler cows has taken on new significance in the post-BSE era.

Policy and livestock systems

The development of livestock systems depends not only on their biological components, but also the economic, social and policy frameworks. In collaboration with economists and social scientists we aim to determine the influences of policy on future development of livestock systems in the European Union and in other parts of the world.

The Land Use Options for Animals Programme links closely to other parts of the Institute's programme of research. Information from the Natural Heritage Management - Vegetation Dynamics (PU27) and Herbivore Foraging Programmes (PU28) are used in the development of some of the principles on which research on grazing systems is based, and models and concepts developed in these programmes are incorporated as sub-models within models of grazing systems. Models of grazing systems are also incorporated into decision support tools which are built as part of the Integrated Programme Unit Development of Decision Support Tools (IPU38). Increasingly the policy framework within which livestock systems operate is being researched in collaboration with colleagues from the Socio-Economic and Policy Analysis Programme (PU22). Whilst the aim of the programme is to identify Land Use Options for Animals, the options which exist for utilisation of land and vegetation resources by animals need to be set against the wider range of options which exist for land use, and this is done within the Geographical and Resource Analysis Programme (PU21).

The specific objectives of the Options for Animals Programme are:

Current Research

- To quantify the heritabilities of, and genetic correlations between economically important traits in cashmere goats and to develop and test selection indices for improving fibre quantity and quality.
- To develop a new genotype of fine-wooled sheep suitable for the production of high quality, high value wool from marginal lands.
- To investigate the effects of environmental cues (photoperiod, temperature, nutrition) on the growth and shedding of fibre by goats.
- To investigate the control of hair follicle activity in goats.
- To develop techniques for the assessment of welfare of ruminant animals and to gain an understanding of the physiology, endocrinology and immunology of stress.
- To study the welfare of farmed red deer during transport and prior to slaughter.
- To quantify the effect of rearing environment on the subsequent welfare of weaned lambs.
- To determine the degree to which complementarity of grazing by different ruminant species is influenced by heterogeneity of the grazed sward.
- To develop theoretical models of mixed grazing systems which can incorporate sociality and foraging theory.
- To investigate genotype x environment interactions in grazing beef cattle.
- To determine how livestock policy is appraised and evaluated by the European Commission and different member states of the European Union.

Achievements

- Cashmere production increased by 7% per annum by genetic selection.
- Average fibre diameter in the new Bowmont breed of sheep reduced to 20 µm.
- Development of the secondary follicles in goats is influenced by photoperiod *in utero*.
- IGF-1 influences hair follicle activity in goats.
- Important role of thyroid hormones in cashmere production identified.
- New automatic blood sampling equipment developed to operate in response to a remote triggering device.
- Lambs reared in extensive hill systems with little human contact are relatively insensitive to degree of human contact after weaning.
- New methods developed for integrating social and foraging behaviour in models of grazing systems.
- Greater effects of complementary grazing at taller sward heights.
- Survey of livestock policy appraisal and evaluation in European Commission and National Ministries of Agriculture completed.

Current Research

Animal fibre biology

The Scottish Cashmere Goat was developed in collaboration with the Roslin Institute to provide a breed of goat, producing high quality cashmere, but which was suited to European conditions. It was originally based on the Scottish Feral Goat, which was crossed with genetic material from Iceland, New Zealand, Tasmania and Siberia (Bishop and Russel, 1996). The quality of the fibre produced by the Scottish Cashmere Goat, in terms of fibre diameter, is comparable to much of the cashmere imported into the UK from China and Mongolia. It is considerably better than that produced in Australia and New Zealand (Hopkins, 1993) where the genetic make-up of the goats used in the initial establishment of these herds included animals with coarser fibre. Our goats have now been exported to Spain, Italy and the Falkland Islands.

The data on heritabilities and genetic correlations produced by MLURI have recently been used by Spanish scientists to explore options for different genetic selection strategies in cashmere goats (Diaz *et al.*, in press). Over the past 5 years the Institute's herd has been used in a genetic selection experiment, where there have been 3 selection lines: a) selected for maximum value of cashmere produced (the selection index was based on both weight of cashmere produced and fibre diameter), b) selected for low fibre diameter and c) a randomly-bred control line. After 5 years of selection, the goats in the line selected for maximum financial return produced 50% more fibre than the control line with no increase in fibre diameter. In the goats selected for reduced fibre diameter, the fibre diameter was reduced by 9%, but this was accompanied by a decrease in cashmere production of 38% (Figure 1). We have concluded therefore that selection for reduced fibre diameter is not, at this stage, economically viable, but selection for increased value of cashmere produced will continue.

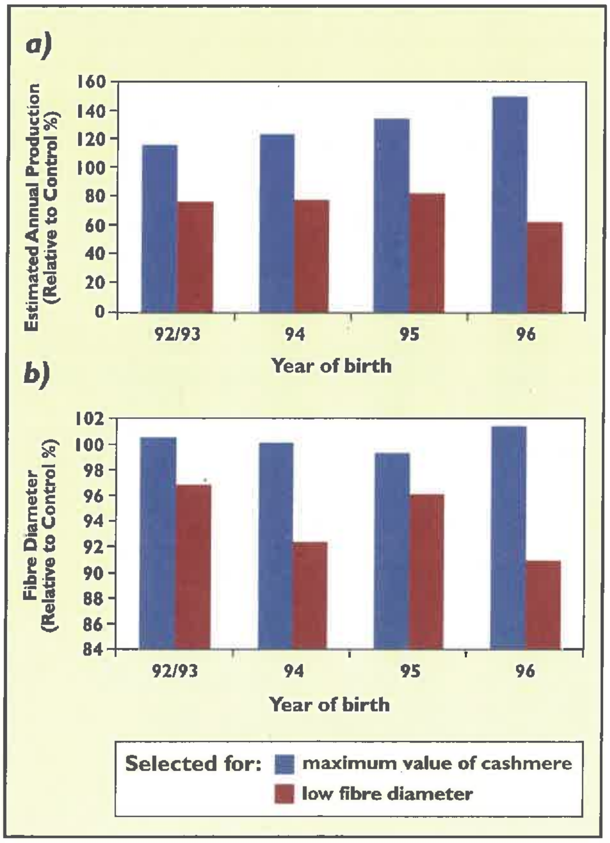

Figure 1. Change in (a) cashmere production (estimated annual prediction) and (b) diameter, 1992 to 1996.

An important finding has been the observation that the photoperiodic signal before or at the time of birth affects the moult of the first kid coat. The secondary hair follicles (those that produce cashmere) are not fully developed in goats at birth and the first undercoat does not normally moult in kids until the increase in daylength in spring when they are one year old, although the guard hair, produced by the primary follicles which are mature at birth, normally moults in summer. It was hypothesised that the insensitive, secondary follicles could not respond to the long daylength in summer, while the mature, primary follicles could, and therefore shed their fibre. An experiment in which pregnant does were exposed to long, short or natural daylength in late pregnancy and then their kids were exposed to long days after birth showed that the secondary follicles of those kids exposed to long days *in utero* moulted, but the others did not (Figure 2). This suggests that follicle development can be influenced by photoperiod *in utero*. The results also explain the observation by Spanish scientists that cashmere kids born in Spain in January moult their kid coat of cashmere in summer - the secondary follicles are mature enough in these kids to respond to the long daylength in summer.

Previous research (Dicks *et al.*, 1996) identified for the first time that there were receptors for insulin-like growth factor-1 (IGF-1) in the skin of goats. This work has been extended, and using techniques for the culturing of hair follicles *in vitro*, it has been shown that IGF-1 influences the rate of growth of fibre in cashmere goats. However the effect is dependent on the time of year and the presence of prolactin. We have therefore concluded that IGF-1 may be involved in the seasonal control of the hair follicle cycle, but its exact role remains to be determined.

Much of the research on cashmere production was linked to a recently-completed research programme funded by DGVI of the European Commission on

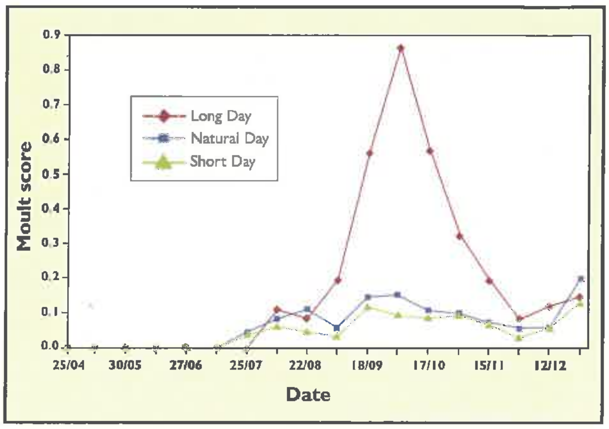

Figure 2. Moult score in kids exposed to different photoperiods in utero.

'Research on the production of high quality cashmere and its potential for agricultural diversification' which involved researchers in Germany, Italy, Spain and the University of Edinburgh.

Animal behaviour and welfare

Much research which has been conducted on animal welfare has concentrated on intensively managed animals, since this has been the primary focus of public concern. However animals managed in extensive systems may also potentially be exposed to stressful conditions. This is particularly the case for animals which may receive little human contact, or novel farmed species. Within the UK, few research groups are tackling the issue of animal welfare in extensive systems, but increasingly consumers are demanding products from 'extensive' systems without there necessarily being a sound scientific basis for such demands. Our work is aimed at developing techniques for the study of welfare in extensive systems. Considerable progress has been made in developing equipment which can automatically collect blood and infuse substances into animals without the need for handling the animals. The original automatic blood sampling equipment (ABSE) developed at MLURI has now been modified so that it can be triggered remotely, using a telemetry system. It has also been used to conduct adrenocorticotrophic (ACTH) stimulation tests in sheep and red deer and it has been demonstrated that the results are comparable with conventional, manual infusion and collection of blood samples (Ferre *et al.*, in press; Figure 3). The equipment opens up new possibilities for studying the physiology of stress in circumstances where handling the animals is either undesirable or impossible and has already been used in collaborative studies on reindeer and cattle in Norway, Sweden and Finland as well as with the Universities of Edinburgh and Bristol.

A large project aimed at studying the welfare of farmed red deer during transport and prior to slaughter has recently been completed. This study, which complemented research conduct at Ruakura, New Zealand (Jago *et al.*, 1997), where deer farming is an important part of agriculture, used a range of behavioural and physiological techniques to provide objective information on which to base potential codes of practice or legislation on the welfare of farmed deer (Grigor *et al.*, 1997; in press a and b). One important question was whether deer should be kept in lairage prior to slaughter alongside other farmed species. In a series of experiments it was shown that red deer showed adverse physiological and behavioural reactions when penned near to other species especially cattle and pigs (Abeyesinghe and Goddard, 1997; Abeyesinghe and Goddard, in press). We concluded that deer should not be kept in the same abattoir lairage as other farmed species.

It is generally thought that the hormone cortisol acts to depress the activity of the immune system (Griffin, 1989). However some of our recent research has suggested that cortisol *per se* may not always be immunosuppresent, but that the pattern of release of cortisol may be important.

Grazing systems

A new modelling framework (HOOFS - Hierarchical Object-Oriented Foraging Simulator) has been developed within which the foraging of mixes of animal species can be simulated (Beecham and Farnsworth, in press). The model simulates the foraging of animals in a patchy environment using a novel approach of combining foraging theory with social behaviour. Using a marginal value calculation the patch residence time is determined, and each animal is then simulated to choose the next patch to move to by combining information on expected net rate of intake, subject to a controlled degree of random variation (biased diffusion) and proximity to other animals (either of the same or a different species). Use of the model has shown, at a theoretical level, how the degree of social cohesiveness within a flock/herd interacts with the spatial heterogeneity of the forage resource to influence the variability and ultimately the level of intake (Figure 4).

The model described above relies on the marginal value theorem for determining patch residence time.

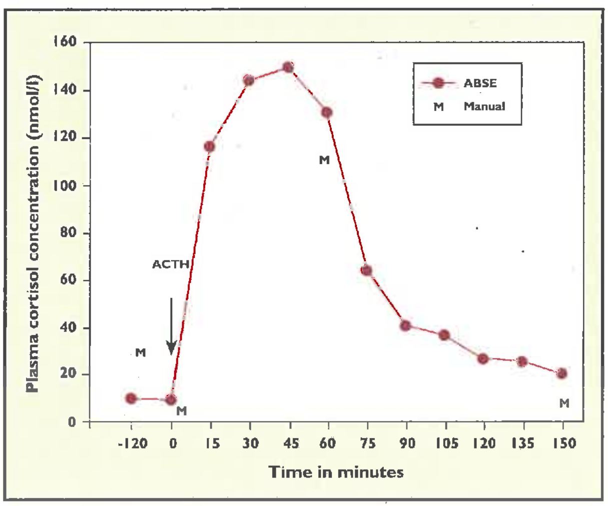

Figure 3. Results from ABSE and manual ACTH - stimulation test.

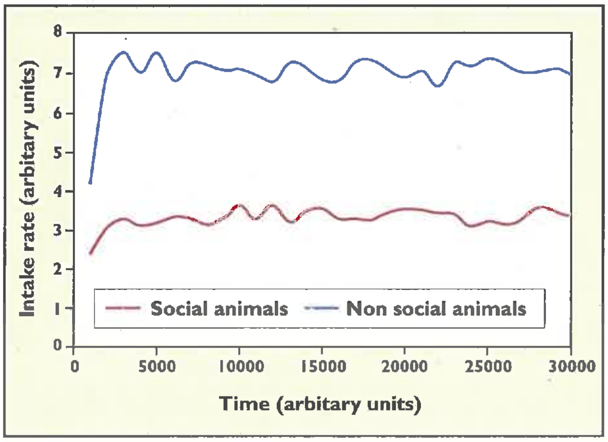

Figure 4. Results of HOOFS simulation.

Sward height							
	4-5cm			8-10cm			
	Cattle only	Cattle plus sheep	Sheep only	Cattle only	Cattle plus sheep	Sheep only	s.e.d
Steers	1.08	1.07	-	1.14	1.14	-	0.081
Ewes	-	0.092	0.073	-	-	0.069	0.0129
Lambs	-	0.260	0.250	-	-	0.212	0.0144

Table 1. Live-weight gain (kg/day) of steers, ewes and lambs in a mixed grazing experiment at Bronydd Mawr

For the model to be developed to the stage of being quantitative for the prediction of the intake and behaviour of sheep and cattle in mixed grazing systems, the marginal value theorem needs to be quantified for cattle and sheep. While some limited studies have been conducted in the USA (Laca *et al.*, 1993) there have been no comparative studies between sheep and cattle. Current research is aimed at determining whether the marginal value theorem can successfully predict differences between sheep and cattle in patch residence time.

In collaboration with the Institute of Grassland and Environment Research experimentation has been conducted to explore the hypotheses that the scope for complementary grazing between sheep and cattle increases as the degree of heterogeneity in the vegetation resource increases. In an experiment where cattle only, sheep only or cattle plus sheep grazed either a short (homogeneous) or tall (heterogeneous) sward, lamb live-weight gain was higher in the mixed, compared to the sheep-only treatments on the tall but not the short swards (Table 1) suggesting that the scope for complementarity between sheep and cattle increases with heterogeneity in the sward. This may in part explain the range in results obtained in experiments on mixed grazing over the past few decades - the degree of complementarity may depend on the heterogeneity of the vegetation resource.

The fact that the lambs from the mixed grazed, tall sward grew at over 30g/day faster meant that they could be sold for slaughter sooner, thus releasing scarce grass in autumn to provide additional feed for ewes prior to mating.

Policy and livestock systems

The options that exist for utilisation of land and vegetation resources depend not only on the biological components of the system, but also on the policy framework. Within the European Union, the Common Agricultural Policy has a large influence on the way in which land resources are deployed. The European Livestock Policy Evaluation Network (ELPEN) funded by the European Commission and coordinated by MLURI seeks to assess the feasibility of developing a framework for appraisal and evaluation of the economic, social and environmental impacts of livestock policy. The first activity of the Network has been to carry out research on the current methods of appraisal and evaluation of livestock policy by the European Commission and National Ministries of Agriculture (Crabtree and Williams, in press).

Future Developments

Animal fibre biology

While there is a continued need to increase, by genetic selection, the quantity of cashmere produced, the genetic parameters required for the construction of selection indices have been quantified and selection indices tested. There is now a need to consider genetic aspects of fibre quality such as lustre, and genetic control of date of shedding, which influences the optimum time for harvesting. Research is now in place to investigate the potential genetic control of lustre and date of moulting and will form an important part of our future research programme. The research is unique to MLURI, but has international significance, given the importance of cashmere production in large parts of Asia.

Little is understood about the control of hair follicle activity. While research in New Zealand identified prolactin receptors in the skin of hair-bearing sheep (Choy *et al.*, 1995) and our own research identified for the first time IGF-1 receptors, it is now clear that these hormones interact at the level of the hair follicle. Recent research has suggested that the thyroid hormones may also be involved in the seasonal control of hair follicle activity, and new research will use a combination of *in vitro* culture techniques and *in vivo* studies to investigate the potential interaction between the thyroid hormones and other endocrine and paracrine influences.

Animal behaviour and welfare

The behavioural needs of an animal change according to its internal state and environmental cues, and are controlled by the animal's motivation to perform those behaviours. Both the animal's feeding behaviour (and therefore performance) and its welfare will be influenced by the extent to which it can express behavioural needs. An understanding of motivation is essential if systems of animal management are to be developed which take account of the animal's behavioural priorities. As yet a generally accepted method for the quantitative assessment of motivation in ruminants is not available, although certain methods have been used to answer specific questions on avoidance, particularly in sheep (Rushen *et al.*, 1990) and deer (Pollard *et al.*, 1994; Wright and Milne, 1996; Grigor *et al.*, in press c). We will therefore develop tests which are suitable for assessing motivation in ruminants. Specifically there is a need to determine which aspects of feeding behaviour are the most sensitive indicators of motivation to feed, and how motivation to feed and to seek social companionship changes as a consequence of both the animal's internal state and environmental cues.

In extensive systems of management the degree of contact between animals and humans is often limited. When animals reared and managed under such circumstances are handled for management purposes they may be placed under considerably more stress than animals reared in more intensive systems. However little is know about the effects of rearing different species under a range of intensities of management on their subsequent response to humans. Comparative studies between red deer (a recently domesticated species) and sheep (which have been domesticated for centuries) are planned. These will investigate the effects of the intensity of the system of management on the response to humans with the ultimate view of developing improved handling and management system for extensively managed livestock. The results of this research should lead to recommendations which will safeguard the welfare of animals.

Grazing systems

If theoretical methods of mixed grazing systems are to be developed into predictive models there is a need to parameterise them for the animal species and environments of interest. The HOOFS model described earlier will be parameterised for sheep and cattle. This will require conducting experiments to establish the functional response curves for intake by sheep and cattle and then testing to see if the marginal value theorem can predict the patch residence time for the two species. This will lead, for the first time to the development of predictive models of mixed grazing systems for sheep and cattle.

New research at Bronydd Mawr Research Centre funded jointly by the Ministry of Agriculture, Fisheries and Food and the Scottish Office Agriculture, Environment and Fisheries Department, in collaboration with the Institute of Grassland and Environmental Research will examine how growing cattle of different genotypes utilise sown and semi-natural vegetation. This will include an assessment of the impact on the vegetation as well as measurement of animal performance. The ultimate aim is to develop efficient systems of producing high quality beef from upland resources.

Environmental oestrogens

The European Commission Urban Waste Water Treatment Directive prohibits the disposal at sea of sewage sludge from the end of 1998. This will result in more sewage sludge being deposited on land. Sewage sludge is known to contain relatively high concentrations of substances with oestrogenic activity (xenoestrogens). However nothing is known about the potential impact of the ingestion of these compounds by livestock which graze land treated with sewage sludge. Accordingly, research started in 1997 will examine the uptake of xenoestrogens by sheep grazing pasture treated with sewage sludge and their transfer into animal tissues. This will complement research in the Soil Quality, Contaminated Land and Waste Utilisation Programme (PU24) on the effects of sewage sludge application on soil processes.

Policy and livestock systems

The work of the European Livestock Policy Evaluation Network will be extended to develop a protocol for the appraisal and evaluation of livestock policy. The feasibility of constructing a framework within which the regional variation in livestock systems can be described, and in which the impact of policy change can be evaluated will be assessed.

The policy-related research will also be extended into the Central Asian States of the former Soviet Union. In collaboration with social scientists from the Overseas Development Institute, research funded by the UK Department of International Development will examine the potential impact of changes in land tenure systems in Kazakstan and Turkmenistan on rangeland management and livestock systems.

Relevance to End Users

A number of methods are employed to ensure that our research is relevant to, and accessible by, end users. Much of the research on cashmere is conducted on animals owned jointly by Cashmere Breeders Ltd (a producers co-operative). Members of staff are Directors of Cashmere Breeders Ltd and Goat Meat Producers (Scotland) Ltd and on the council of the Scottish Cashmere Producers Association. This ensures close liaison with cashmere producers and continued dialogue with them. MLURI also co-ordinates the European Fine Fibre Network, a network of researchers, producer organisations and textile companies. By means of the activities of this network (workshops, newsletters), the results of research are disseminated to a wide range of interested parties in Europe and beyond, in Asia, Australasia and North America and MLURI is seen as a major European centre for research on cashmere and fine wool. Our research also has a direct impact on cashmere producers in Scotland as superior animals, bred as a direct consequence of our research to produce cashmere to meet the criteria set by the textile industry, are distributed to members of Cashmere Breeders Ltd.

Results of research on animal welfare are reported directly to Government Departments to allow decisions about legislation and/or codes of practice to be taken against a background of sound scientific evidence. For example, results of research on the effects of keeping farmed red deer in lairage with other species showed that the recommendation in the Code of Practice that red deer should not be kept in lairage with other species should not be modified.

The theoretical research on modelling grazing systems is such that at this stage the users of the results are mainly other scientists, both inside and outside MLURI. However the concepts being developed have generated considerable interest in France (INRA) where joint experiments are being planned to test some of the assumptions used in the modelling process. Ultimately this research will lead to new predictive models of mixed grazing systems which can be incorporated into the next generation of decision support tools for grazing systems.

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Understanding the interactions between soils, plants and animals in terms of nutrient cycling is important for achieving a variety of conservation, production and environmental objectives, thereby enabling assessments of the sustainability of land use to be made.

Soil-Plant-Animal Interactions

Upland pastures support natural and semi-natural grasslands grazed by sheep, cattle and goats. Pasture productivity is governed by the cycling of nitrogen and phosphorus in soils. Developing management strategies for these systems, which balance productivity with achieving environmental objectives, requires an understanding of the processes regulating soil nutrient cycling and how grazing animals affect these processes. Management of upland pastures is often regarded as being 'extensive', i.e. involving minimum fertiliser inputs. Understanding the interactions between soils, plants and animals in terms of nutrient cycling is, therefore, important for achieving a variety of conservation, production and environmental objectives, thereby enabling assessments of the sustainability of land use to be made.

In studying the impact of both vegetation and grazing animals on soil nutrient cycling at a strategic level, we are underpinning studies of vegetation dynamics, plant ecophysiology and soil chemistry elsewhere in the Institute's programme. A key feature of our research is our ability to bring together a multidisciplinary team comprising plant physiologists, soil microbiologists and soil chemists. The programme links with others studying plant and animal ecology, plant physiology and soil chemistry, thereby creating the multidisciplinary base needed to consider the wider interactions between soils, plants and animals in grazed pastures.

The programme is in line with the recommendations of the recent Technology Foresight Panel on Agriculture, Natural Resources and Environment which recommends that both Integrated Ecosystem Management and Environmentally Sustainable Technology be research priorities. Furthermore, our research on the interaction between plant roots and soil microbes accords with the 'Priorities in Soil Science Research' recently proposed by the BBSRC/NERC Soil Science Advisory Committee.

Strategic Objectives

Upland pastures are characterised by extensively-managed, natural and semi-natural grasslands growing on acid soils of low fertility, which have a high organic matter content. Pasture production is maintained by the cycling of nitrogen and phosphorus, due to the activity of soil microbes. Growth of soil micro-organisms is carbon limited and depends upon plant litter, dead roots and rhizosphere carbon flow. Plant litter and dead roots are most important for the organic matter they supply to soil and its turnover. However, it is the loss of readily-available carbon substrates from plant roots as exudates which has the greatest effect on stimulating the activity of soil micro-organisms. This explains why microbial activity is much greater in the rhizosphere (the soil within immediate vicinity of the root) compared with the bulk soil.

Grazing animals can influence the interactions between vegetation and soils in several ways (Figure 1). First, defoliation can alter rhizosphere carbon flow and so alter soil microbial diversity and activity. Secondly, urination can alter the dynamics of nutrients in the rhizosphere by chemical means (as a consequence of increasing soil pH). Thirdly, addition of nitrogen in the urine can affect the competition between microbes and plant roots for nutrient uptake. In the longer-term, enhanced plant growth due to increased nutrient availability can result in greater rhizosphere carbon flow and so alter soil microbial diversity and/or activity.

Our aim is to understand the complex interactions between vegetation and soil microbes and determine how grazing animals alter these interactions. Such an understanding will enable the consequences of different management strategies for upland pastures to be determined in terms of the sustainable cycling of

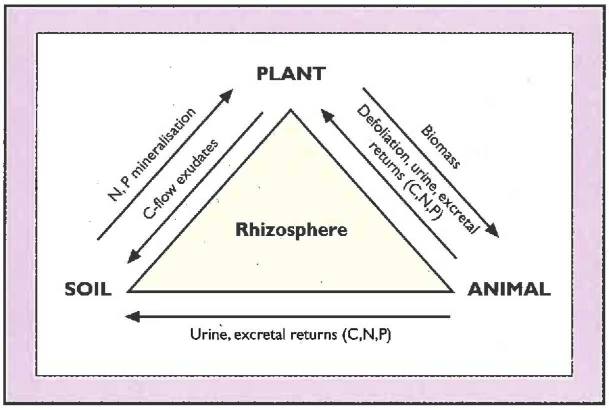

Figure 1. The effect of grazing animals on the interactions between plants and soil microbes which regulate nutrient cycling in upland pastures.

soil nitrogen and phosphorus. This is important in relation to both managing future changes in land use in the uplands (e.g., pasture extensification) and for considering the environmental consequences of management (e.g., nutrient losses from soils).

Our research is linked to studies of soil organic matter and soil microbiology in the programme Soil Quality, Contaminated Land and Waste Utilisation (PU24). There is a close integration between our research on rhizosphere carbon flow, and the study of the ecophysiology of defoliated grasses in the Land Use Options for Plants (PU26) Programme. Our studies also underpin the programme Natural Heritage Management - Vegetation Dynamics (PU27). In addition, our study of urine deposition on soil nitrogen dynamics links to the study of the impact of atmospheric nitrogen deposition in the programme Atmospheric Deposition, Land Use and Water Quality Management (PU23), by contributing to our understanding of the formation and turnover of dissolved organic nitrogen (DON) in soils.

In order to develop strategies for the sustainable management of hill and upland pastures it is necessary to understand the interactions between plants and soil microbes. Our strategic research concentrates upon how both qualitative and quantitative changes in rhizosphere carbon flow from a range of grassland species affects soil microbial diversity and activity. We are collaborating with a range of other organisations in the MICRONET programme, to develop and utilise a range of molecular and physiological techniques to quantify soil microbial diversity and activity (in terms of key processes involved in nutrient cycling such as ammonia oxidation and phosphatase activity). These techniques will be used to assess the degree of coupling between soil microbial and plant communities, in terms of both microbial diversity and activity. These interactions will be studied in relation to both temporal and spatial heterogeneity.

The impact of grazing animals (via defoliation and urine returns) on the soil-plant interactions is being studied. We aim to determine the consequences of these interactions in terms of soil nitrogen and phosphorus cycling in both laboratory and field studies. This will allow us to distinguish between short-term effects of urine deposition on soil chemistry and the longer-term effects on pasture productivity moderated via changes in soil microbial diversity and activity.

Achievements

- Demonstrating the temporal variation in the soil microbial community structure and activity in upland pastures (Grayston, Campbell, Griffiths, Mawdsley and Bardgett, submitted).
- Determining that plant species have a selective effect upon the microbial communities in the rhizosphere (Grayston, Wang, Campbell and Edwards, 1998).
- Establishing that there is an inverse relationship between soil fungal communities and the degree of improvement of pasture systems (Grayston *et al.*, submitted).
- Quantifying changes in soil microbial community structure in response to plant growth under elevated CO_2 (Grayston, Campbell, Lutze and Gifford, submitted).
- Demonstrating that urine application decreases bacterial but stimulates fungal communities in the rhizosphere.
- Determining that regular defoliation of grasses decreases the microbial biomass and alters the microbial community structure due to changes in rhizosphere carbon flow.
- Establishing that urine deposition increases the nitrogen in the soil microbial biomass for up to three months after treatment, meaning that soil N dynamics is regulated by the balance between immobilisation and mineralisation because nitrification is not occurring.
- Quantifying the impact of urine deposition on the dynamics of organic, colloidal and inorganic P in soils as a consequence of short-term changes in soil pH.
- Establishing that defoliation of grasses leads to a reduction in the amount of carbon and phosphorus on soil solution.

Current Research

The impact of grazing on interactions between plants and soil microbes

In upland pastures the availability of nutrients for plant growth is governed by the activity of soil microbes. However, plants can exert a large influence on both the composition and activity of microbes in the rhizosphere. We have developed a method to characterise the diversity of the bacterial community in soils by analysis of their use of different carbon substrates for growth (Grayston and Campbell, 1996; Campbell, Grayston and Hirst, 1997). Using this technique we have shown that plant species have a major selective influence on the soil microbial community structure, through variation in organic compounds they release from their roots. These changes in rhizosphere carbon flow are reflected in different metabolic profiles between microbial communities from the rhizosphere of different plants (Grayston, Wang, Campbell and Edwards, 1998) (Figure 2). Although loss of carbon from plants had been postulated to be a key factor influencing microbial diversity (Grayston, Vaughan and Jones, 1996; O'Neill, 1994), our studies have produced some of the first direct evidence to support this hypothesis. An example of the significance of this finding is in considering how vegetation will respond to increasing atmospheric CO_2 concentrations. The availability of nitrogen has been shown to be particularly important in determining the magnitude of plant response to elevated CO_2 (Bowler and Press, 1993, 1996; Rogers *et al.*, 1996), and in a low-nutrient environment the activity of soil microbes will be important in regulating the supply of nitrogen to plant roots. Previous studies on the effects of elevated CO_2 on soil microorganisms have produced conflicting results (e.g., Diaz *et al.*, 1993; O'Neil, 1994; Zak *et al.*, 1996 and Runion *et al.*, 1994). However, in collaboration with CSIRO, Canberra, we have shown that microbial community structure in the rhizosphere of grasses changes when the plants are grown with elevated CO_2, the first study to demonstrate such a change (Grayston, Campbell, Lutze and Gifford, submitted). These changes in microbial diversity were due to grass roots exuding compounds with a higher C:N ratio when grown with elevated CO_2.

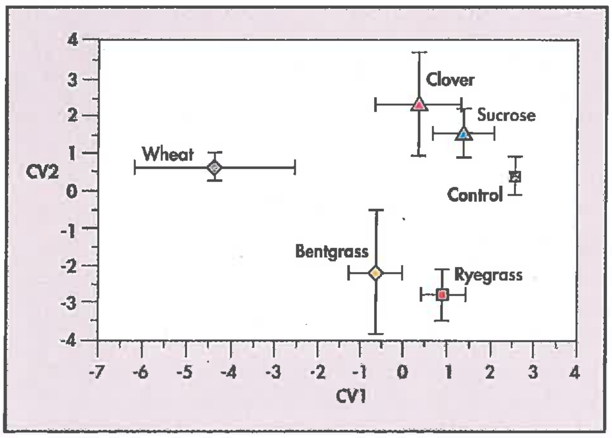

Figure 2. Carbon utilisation profiles of microbial communities in the rhizosphere of different plants

Figure 3. The distribution of field sites (red) used in the MICRONET project and the location of the collaborating organisations (black).

From our studies it is clear that vegetation can have a profound influence upon both the diversity and activity of the soil microbial population. We are studying the links between plant and soil microbial communities as part of the coordinated MICRONET project referred to earlier. This project, involving collaboration with the Scottish Crop Research Institute (SCRI), the Scottish Agricultural College (SAC), the Institute of Grassland and Environmental Research (IGER), and the Universities of Aberdeen, Lancaster and Manchester, aims to quantify the spatial and temporal diversity of microbial communities beneath characteristic grassland types (unimproved, semi-improved and improved) at ten sites throughout Britain (Figure 3). This is a unique programme, of international significance, because it is developing and applying a wide range of molecular and physiological techniques to the same soil samples, to assess microbial diversity. These techniques range from molecular approaches such as 16s rRNA sequence analysis, DNA melting profiles, reassociation kinetics and DNA-to-DNA hybridisation studies, through physiological studies of microbial carbon substrate utilisation and phospho-lipid fatty acid profiling, to the classical culturing techniques. In addition to providing an unique insight into the impact of vegetation on soil microbial communities, this ten year programme will allow us to assess the utility of these different approaches and their sensitivity in detecting changes in the microbial community. There is no other similar programme anywhere in the world.

As part of our contribution to MICRONET we have shown that there is an inverse correlation between microbial biomass and fungal communities, and a direct correlation between bacterial communities and the degree of pasture improvement. Overall, the diversity of the microorganism decreases with increasing management intensity (Grayston, *et al.*, submitted). We have also demonstrated that differences in microbial communities between pasture types and sites are robust over time, but vary quantitatively in parallel with plant productivity (Figure 4) (Grayston, *et al.*, submitted).

In many grassland ecosystems, grazing by herbivores may be the key determinant of microbial activity, through alteration in rhizosphere carbon flow as a result of defoliation (Holland and Detling, 1990) and through a rapid return of nutrients to the soil as dung and urine (Seagle, McNaughton and Ruess, 1992). However, few studies have linked these processes (Ruess and McNaughton, 1987). We have established experiments which link closely to research on the consequences of defoliation on grass ecophysiology (in our Land Use Options for Plants Programme, PU26).

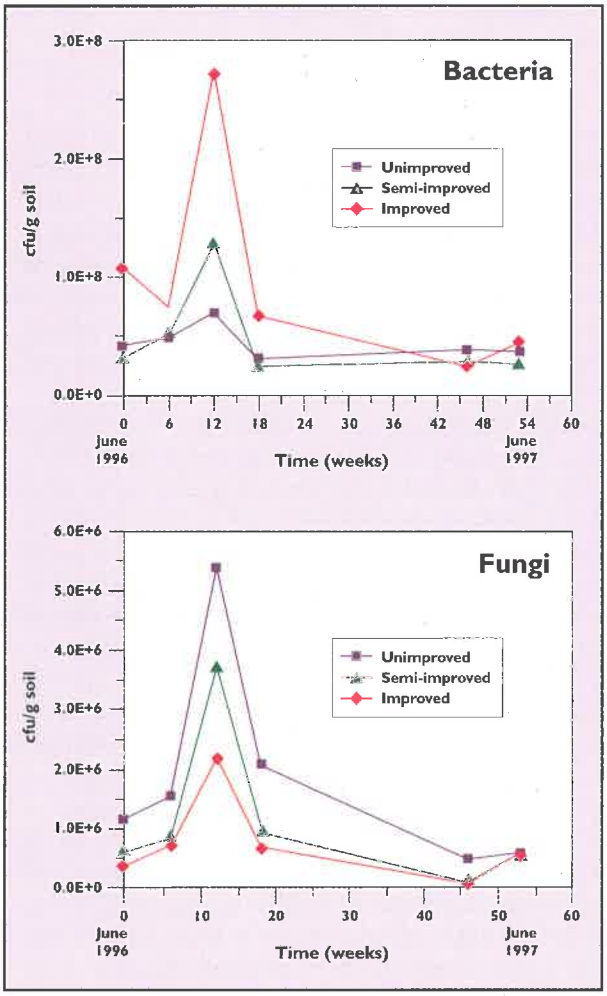

Figure 4. Variations in the soil bacterial and fungal population from different types of pasture during the course of a year.

Growing grasses in sward boxes we have studied root topology and turnover in relation to soil microbiology and the dynamics of nitrogen and phosphorus in the soil. Application of sheep's urine and defoliation of the grasses has been used to simulate grazing by sheep.

We have determined that regular defoliation of grasses decreases the soil microbial biomass and alters microbial community structure due to changes in rhizosphere carbon flow. We have also demonstrated that urine application decreases fungal but stimulates soil bacterial communities and the total microbial biomass in the rhizosphere. Previous studies have shown a decrease in microbial biomass in the rhizosphere when grazing sheep are removed from pastures (Bardgett *et al.*, 1997), which was suggested to be due to decreases in rhizosphere carbon flow due to a cessation of defoliation. However, our studies show that it is the reduction in nutrient inputs from urine which reduces the microbial biomass in ungrazed systems. Additionally, we have shown that rhizosphere carbon flow is in fact decreased, not increased, as a result of defoliation. This finding contrasts with previous studies (Waters and Borowicz, 1994), and highlights the fact that nitrogen supply (as well as carbon) is a rate-limiting factor for microbial growth in soil as also found in our study of microbial responses to elevated CO_2 (Grayston, Campbell, Lutze and Gifford, submitted).

In grazed pastures the availability of nitrogen for both soil microbes and plants is largely governed by urine deposition. The amount of nitrogen deposited within a single urine patch by sheep can be equivalent to 400-510 kg N ha^{-1} (Thomas *et al.*, 1988). In contrast to previous studies in Scotland and New Zealand which have concentrated on the fate of urine-N in soil (Thomas *et al.*, 1988; Williams and Haynes, 1994) we have studied the effects of urine deposition on the rates of the different nitrogen transformation processes in the soil. These processes include ammonification and nitrification, and the use of ^{15}N dilution to calculate gross mineralisation and immobilisation of nitrogen. Soil cores treated with sheep's urine in the first week in May at Sourhope and Glensaugh showed significant ($p < 0.001$) increases in the microbial nitrogen pool (Figure 5). The effect was first detected two weeks after application (May 20) and was still present after three months. The soil microbial biomass was greater at Sourhope than Glensaugh and the response to urine application indicated immobilisation of urea-N by microbes in both soils. We are studying these processes in both sward-box and field experiments. In contrast to previous studies our experiments are studying soils under semi-natural vegetation such as *Agrostis-Festuca* grassland (National Vegetation Classification U4B) which are extensively-managed and where we know that microbial diversity is greater but activity reduced compared with improved, more intensively managed *Lolium* grasslands (Grayston, Campbell, Griffiths, Mawdsley and Bardgett, submitted). The soils we are studying are more acid (pH < 4) and contain higher levels of organic matter than those beneath intensively-managed pastures and acid-sensitive processes such as nitrification are either intermittent or inactive (Morecroft et *al.*, 1994). In order to determine which factors control the activity of ammonium oxidising bacteria in these soils, collaboration with Aberdeen University has been initiated to deploy molecular probes for ammonia oxidation in our experiments (Kowalchuk et *al.*, in press).

Another novel aspect of this work is the study of the role of dissolved organic forms of carbon (DOC) and nitrogen (DON) in these soils, which we have shown contain appreciable amounts of both. Recent work has shown that moss vegetation can release DON (as amino acids) in response to additions of inorganic NH_4NO_3 (Williams and Silcock, 1997). We are developing models of carbon and nitrogen cycling in grassland soils to incorporate DOC and DON pools into existing models (Figure 6), in collaboration with INRA, Clermont-Ferrand. These studies on DON have important implications for managing vegetation which can utilise low molecular weight amino acids. This work, therefore, will link closely to research planned in the Land Use Options for Plants Programme (PU26) which will study amino acid uptake and utilisation by grasses.

In addition to influencing soil nitrogen dynamics, urine deposition can also directly affect soil phosphorus cycling. There have been few studies of the release of P by addition of nitrogenous compounds to soil (Hartikainen, 1996). In sward box experiments we have shown that adding sheep's urine caused a rapid increase in pH of the soil solution, which reached a maximum around two days after the application. Coupled with this there was a hundred-fold increase in the concentration of P in the soil solution between 2-14 days after treatment. Much of the P recovered in soil solution from upland pastures is in an organic-complexed form (Shand, Macklon, Edwards and Smith, 1994 and Shand and Smith, 1996). We found that most of this increase in soil-solution P after urine addition was in organic and polyphosphate forms. We have studied the release of these forms of P in grazed pastures in field experiments at Sourhope and Glensaugh. Application of sheep's urine to soil cores at these two sites had contrasting effects on soil solution P chemistry. At Sourhope there was little or no increase in soil solution P concentrations at any time after addition of urine, while at Glensaugh we found a similar increase as reported above in our sward box experiments. The differences between soil P dynamics after urine deposition to these two soil types we think is related to the extent of nitrification, which converts ammonium to nitrite with the release of a proton. The buffering capacity of the soil and sorption characteristics for ammonium by the soil minerals will also need to be considered.

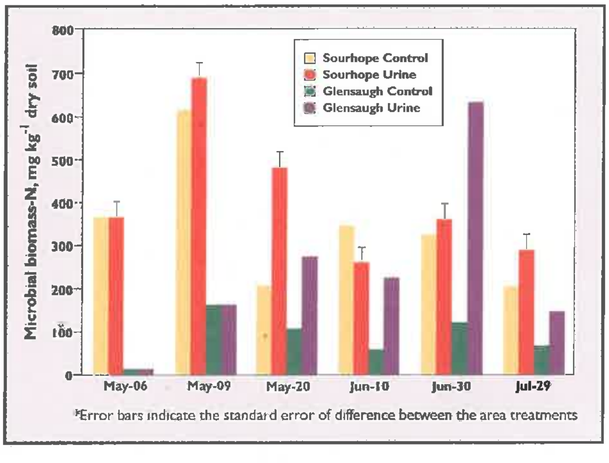

Figure 5. The effects of urine addition to soil at Sourhope and Glensaugh on the nitrogen contained within the soil microbial biomass.

Increasing soil pH in a urine patch can be expected to disperse colloidal matter into the soil solution. Field Flow Fractionation methods have been developed in collaboration with Monash University (Australia) to study the movement of colloidal P in soils. We are using these techniques to analyse soil solutions from urine patches in order to study the dynamics of colloidal P (predominantly polyphosphates). This work is important in determining both the availability of P for uptake by plants and microbes, and the loss of colloidal P from soils, and links closely to work on soil P dynamics in our Soil Quality, Contaminated Land and Waste Utilisation Programme (PU24).

Future Developments

Study of soil microbial diversity and activity in relation to vegetation will be extended within the MICRONET programme. A collaborative experiment will be established to prepare monocultures of either *Lolium perenne* or *Agrostis capillaris* in soils which have previously supported a mixed, unimproved sward dominated by *Agrostis* and *Festuca*. This experiment will be established at Sourhope, which has also been selected as the field-site to be used by the new NERC Thematic Programme on Soil Biodiversity. Siting these two initiatives together should produce excellent opportunities for further collaboration with other groups in the UK. In the MICRONET experiment we propose to follow changes in soil microbial diversity and activity consequent of the changes to a single species of plant. The full range of techniques developed in the first phase of MICRONET will be applied to soil samples taken from the experiment. This will enable us with our collaborators to make a full comparison between the different physiological and molecular techniques we have so far developed for monitoring soil microbial diversity and activity. In addition, we will be able to examine the degree of coupling between individual plant species and the microbes in their rhizosphere by quantifying temporal shifts in the composition of the biomass resulting from a change from mixed vegetation to a single species.

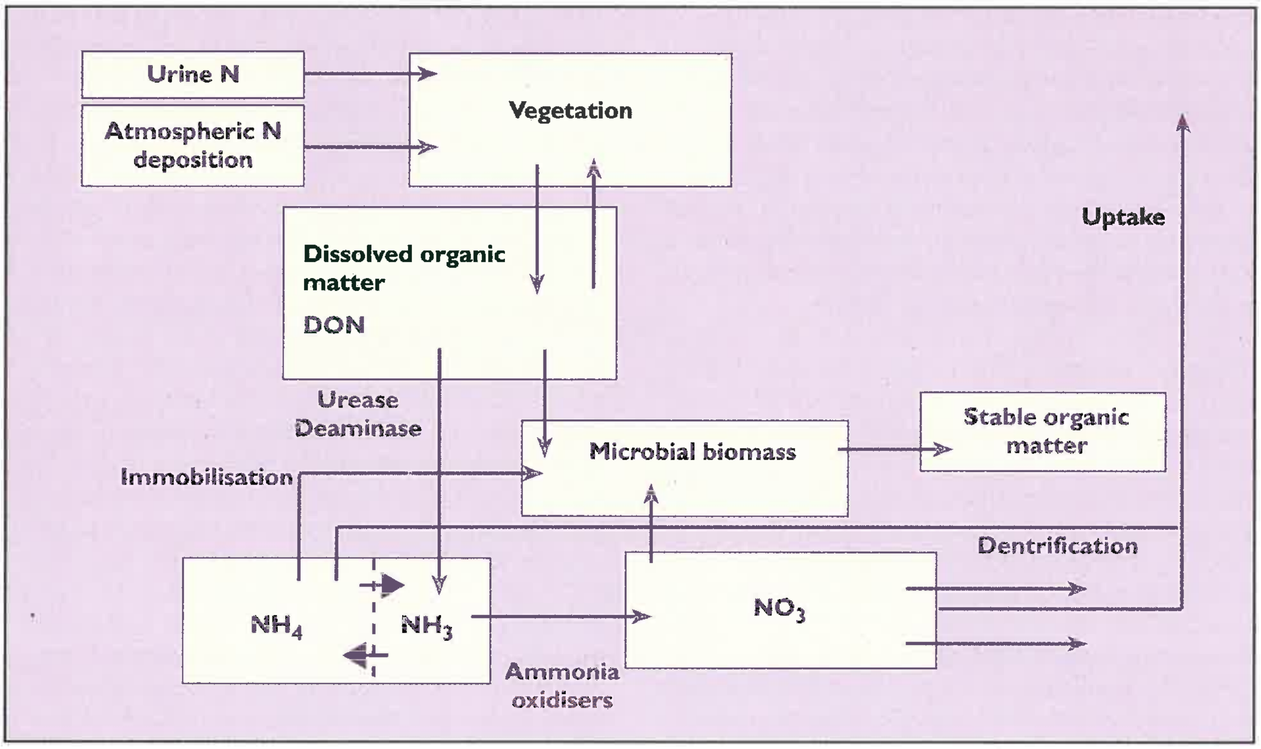

Figure 6. Conceptual model of the role of dissolved organic nitrogen (DON) in relation to plant uptake, microbial biomass and nitrogen transformation processes.

Research on rhizosphere carbon flow will continue to use both sterile microcosms we have developed (Hodge, Grayston and Ord, 1996) and plants grown in soil (Paterson, Rattray and Killham, 1996). Study of the impacts of nitrogen supply and defoliation on rhizosphere carbon flow and microbial diversity in the rhizosphere will increasingly link to studies of the ecophysiology of grasses in our Land Use Options for Plants programme (PU26).

The consequences of grazing on the chemistry of pasture soils will continue to develop studies of both nitrogen and phosphorus. The process of nitrogen cycling in relation to DOC and DON will continue to be studied and collaboration with Aberdeen University, utilising molecular biological techniques to quantify the impact of defoliation and urine applications on the activity and distribution of ammonia-oxidising bacteria. Study of soil phosphorus will continue to study colloidal P transfers in soils using Field Flow Fractionation techniques. This work will increasingly link to both the studies of ammonia oxidation mentioned above and other studies of P cycling in soils in our Soil Quality, Contaminated Land and Waste Utilisation Programme (PU24). Collaboration with the Institute of Grassland and Environmental Research will continue to develop Field Flow Fractionation Techniques and apply them in a range of pasture types.

Relevance to End Users

Our strategic research aims to understand the interactions between vegetation and soils in upland pastures, how these interactions regulate nutrient cycling and how grazing animals affect these interactions. The knowledge gained from this research will be important in providing an understanding of how to maintain biodiversity in upland pastures (in terms of both above- and below-ground communities). Developing sustainable management strategies for pastures, which balance productivity with environmental objectives (e.g., biodiversity or landscape creation), requires the understanding of soil-plant-animal interactions arising from our research. The end-users of our research, therefore, are land managers and policy makers, and ultimately society as a whole with respect to 'quality of life' criteria implicit within the concept of sustainability.

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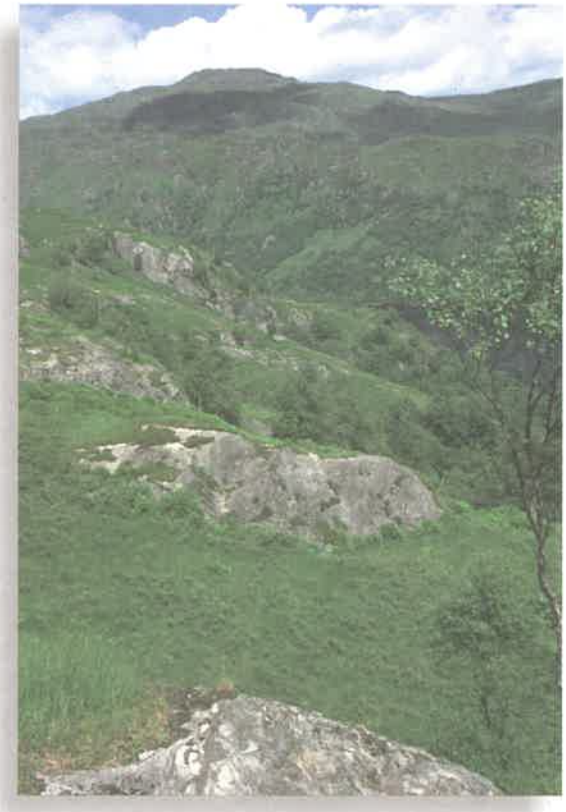

Measurement of the changes in environmental capital is central to our ability to assess sustainability.

Long-term Measurement and Monitoring of Change

A key issue in discussions about environmental sustainability and sustainable development is the change in environmental capital that occurs as a result of land-using activity. This activity can be in the form of agriculture and forestry, water and mineral extraction, abandonment and reduced use of land, or use of land for natural heritage management. External influences, such as atmospheric pollution, and pollution of water courses, soil or the food chain can also cause changes in environmental capital as they relate to the impact on land resources. Measurement of the changes in environmental capital is thus central to our ability to assess sustainability, however it is defined.

This is well recognised by governments in their post-Rio commitments to Sustainable Development and Biodiversity and in their attempts to identify key indicators of environmental change and to put in place monitoring systems to measure change in environmental and land cover variables. The European Union has played a central role in encouraging such monitoring through legislation. In the UK the government has identified a series of key environmental indicators and has introduced a number of monitoring initiatives. In the land use area, one example is the Environmental Change Network (ECN), which is sponsored by a number of government departments, including the Scottish Office, and in which the Macaulay Land Use Research Institute participates through managing two sites in Scotland at its Glensaugh and Sourhope Research Stations. In Scotland it was also recognised that a baseline Land Cover Survey was required as a prerequisite to measuring change and this was undertaken through a full coverage aerial photographic survey in 1988 which was interpreted by staff of the Macaulay Land Use Research Institute. Air and water quality have been monitored in a systematic manner for the past 15 years and the Institute has been involved over this period in measuring atmospheric deposition and water quality in relation to acidification. The efficiency with which policy measures cause change in land management practices, such as the designation of Environmental Sensitive Areas, are also being monitored on behalf of the Scottish Office by the Macaulay Land Use Research Institute and the Institute of Terrestrial Ecology. Moreover the Royal Commission on the Environment report on Soil Sustainability suggested that monitoring of soil quality should be increased.

These various initiatives demonstrate that the Institute has a strong involvement across the whole of its research programme in the measurement of change in land use, land cover and environmental parameters. This has given a clear insight into some of the underlying issues that relate to these measurements. The most important of these issues relate to the variables that should be measured, how they should be measured, with what frequency they should be measured and at what scale they should be measured. Furthermore, there is the question as to whether value can be added by combining sets of measurements and can the cost-benefit of different approaches be improved? The interdisciplinary research in this area aims to address these questions and the extent to which the methodologies developed have a significance which go beyond the particular circumstances of Scotland.

Strategic Objectives

The strategic objective of this programme is to improve the quality of measurement and the monitoring of change in environmental variables by improving current methods with an emphasis on exploring integrative measures in a holistic manner.

More specifically the research focuses on developing a methodology which can be used to update the land resource information which is available for Scotland. This will build on the Land Cover of Scotland 1988 description (Macaulay Land Use Research Institute, 1993). New methods of measuring change in environmental variables at scales relevant to the management unit and to the catchment will be developed. The extent to which measurements made at different scales can be used to provide integrated measures of change and add value to current approaches will also be explored.

The programme links strongly to the research on Geographical and Resource Analysis (PU21) where developments in remote sensing research and spatial and expert knowledge modelling techniques are providing new methods for measuring change in land use. It also links to research on Atmospheric Deposition, Land Use and Water Quality Management (PU23), which is concerned with elucidating the complex changes that occur in water quality in time and space. Changes in the biodiversity of plants is a major theme of research in Natural Heritage Management - Vegetation Dynamics (PU27) and of soils in research on Soil Quality, Contaminated Land Management and Waste Utilisation (PU24): the findings at smaller geographical scales are integrated with other techniques to study change at larger scales. Research in the Socio-Economic and Policy Analysis Programme (PU22) is concerned with environmental and agri-environmental policy analysis. One element of this is the ability to measure land use or environmental change in a cost-effective manner to assist in policy evaluation.

Specific Objectives

- Develop a methodology, based on on-screen land cover interpretation, to simplify the development of a current land cover description for Scotland (a).
- Develop an approach to measure change in the biomass of semi-natural vegetation through the use of remote-sensing technologies (b).
- Model the impact of change in farm management practice on biodiversity at the landscape scale (c).
- Design and test a method for a rapid habitat assessment of the impact of large herbivores on the vegetation at the management unit level (d).
- Monitor the changes in soil erosion and vegetation change associated with grazing at a landscape scale (e).
- Monitor change in a range of physical, chemical and biological variables at the two Scottish sites of the Environmental Change Network (f).
- Explore the cost/benefit of different approaches to the measurement of environmental change (g).

As can be seen from the specific objectives of the programme, there is research on the methodology or measurement of change across a number of geographical scales. This is illustrated in Figure 1. The future aim of the programme is to explore the extent to which more information can be gained by combining observations made at different scales to add value to the measurements of change being made at any one scale. The dotted arrows on Figure 1 indicate some of the possible synergisms that could arise by combining measurements at more than one scale.

A key development this year has been the development in conjunction with Biomathematics and Statistics Scotland of a methodology for identifying trends in runs of environmental data (Miller and Hirst, 1998). As can be seen in Figure 2, this has been applied to a data set on solute concentrations from a stream in an upland catchment at Glensaugh Research Station, one of the Environmental Change Network sites.

Possible changes in the concentrations of solutes in streams could be due to changes in components of atmospheric inputs and flows over time. Graph (a) shows the data over 5 years in which it is difficult to identify trends. Graphs (b), (c) and (d) show that there are independent (b) seasonal trends, (c) time trends with a decline in the concentration of sulphate and (d) effects of stream flow (Figure 2).

Current Research

It is becoming increasingly apparent that, even though the measurement of change can be costly, it is indispensable if we are to understand fully the impact of land use and other activities on the local and global life support systems on which we depend. The need

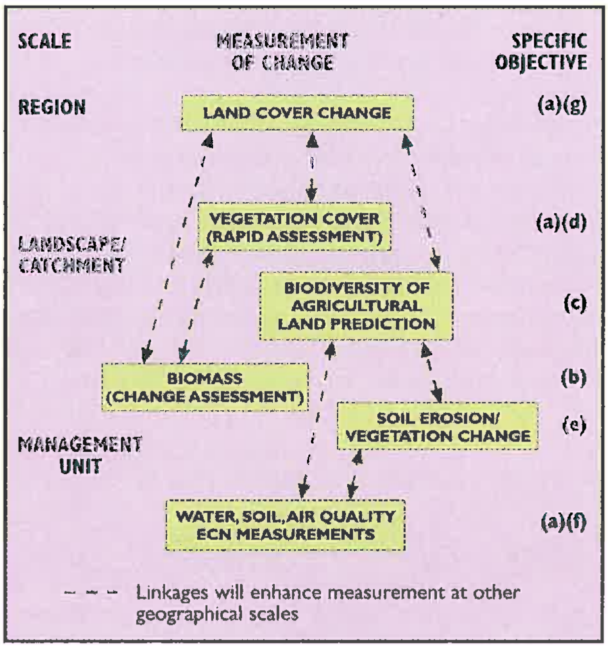

Figure 1. Description of research programme.

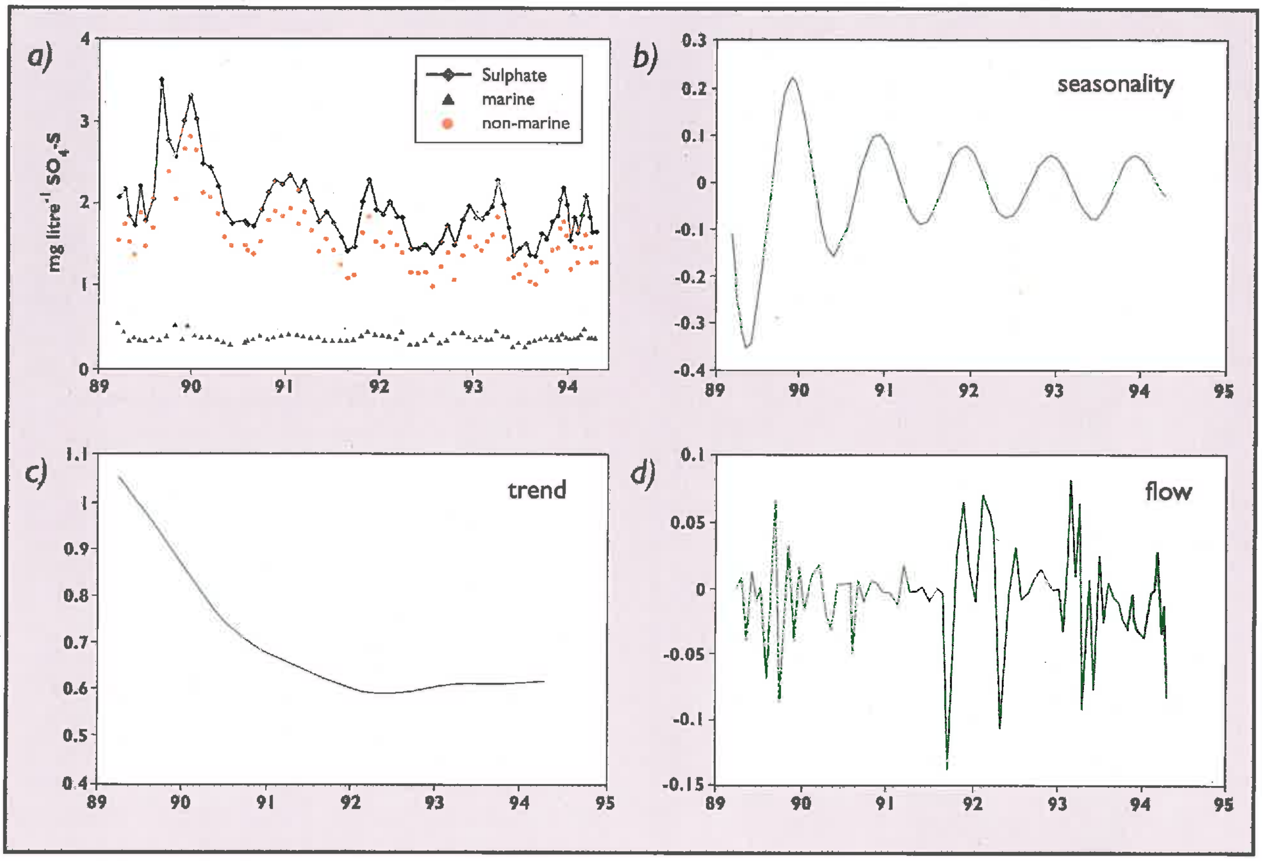

Figure 2. Sulphate-S concentrations in the ECN stream at Glensaugh over the period 1989-94 (2a) - total marine components, derived from chloride, and non-marine concentrations. Variance due to season (2b), trend (2c) and flow (2d) - different scales on y-axes indicate their relative magnitudes.

for governments to monitor the effectiveness of environmental policies in this context, for example, has thrown into sharp relief some of the research issues which need to be tackled with respect to the measurement of change. Frequency of sampling, for example, is a crucial issue in relation to the robustness and reliability of measurement and its cost. Although the methods being used by the Environmental Change Network (Sykes and Lane, 1997) for measuring change in the chemical and physical properties of soils are well tried, it is not clear as to the frequency with which the measurements ought to be made. Current research at MLURI is attempting to answer this question in relation to the variability that exists in soils found in upland areas of the UK to complement research being done by the BBSRC Institute of Arable Crops Research at Rothamsted. The measurement of change in the number of plant species on the ECN sites is expensive to make on an annual basis and hence was planned on a five-year cycle. The Institute of Terrestrial Ecology and MLURI are currently exploring the advantages of making annual measurements. Such issues are common in all such monitoring schemes and, through the Institute's involvement in the Environmental Change Network, there is the opportunity to influence the development and use of new and improved methods world-wide.

The development of rapid and cost-effective methods of describing vegetation cover and biomass is also important throughout the world. Remote sensing has had a central role in the classification and mapping of simple plant canopies since the 1970s, and has been of particular value in broad-scale analysis of land use and land cover change in the tropics (Roderick and Noble, 1998). Only in the last decade in the UK has satellite remote sensing been considered a feasible way of mapping ecologically meaningful plant communities and monitoring semi-natural vegetation resources at a fine scale (Belward *et al.*, 1990). We have been able to use a Landsat Thematic Mapper spectral classification combined with soils and altitude information at the 1:50,000 scale to describe ecologically meaningful vegetation types and their relative biomasses in a vegetation index (Wright *et al.*, 1997) (Figure 3). There is the potential to develop such approaches further by the integration of information from remote sensing and other sources of data to provide enhanced information on vegetation at finer scales by using a multi-scale approach (Lambin, 1998: Matthews, 1998). MLURI has been at the forefront in developing such approaches at the management unit scale in a Scottish context but which is also applicable to other European countries.

The same approach is also being adopted in the development of rapid habitat assessment methods for describing the grazing impact of large herbivores, such as sheep and red deer, on semi-natural vegetation in Scotland. Such information is required to develop plans for the sustainable management of the land

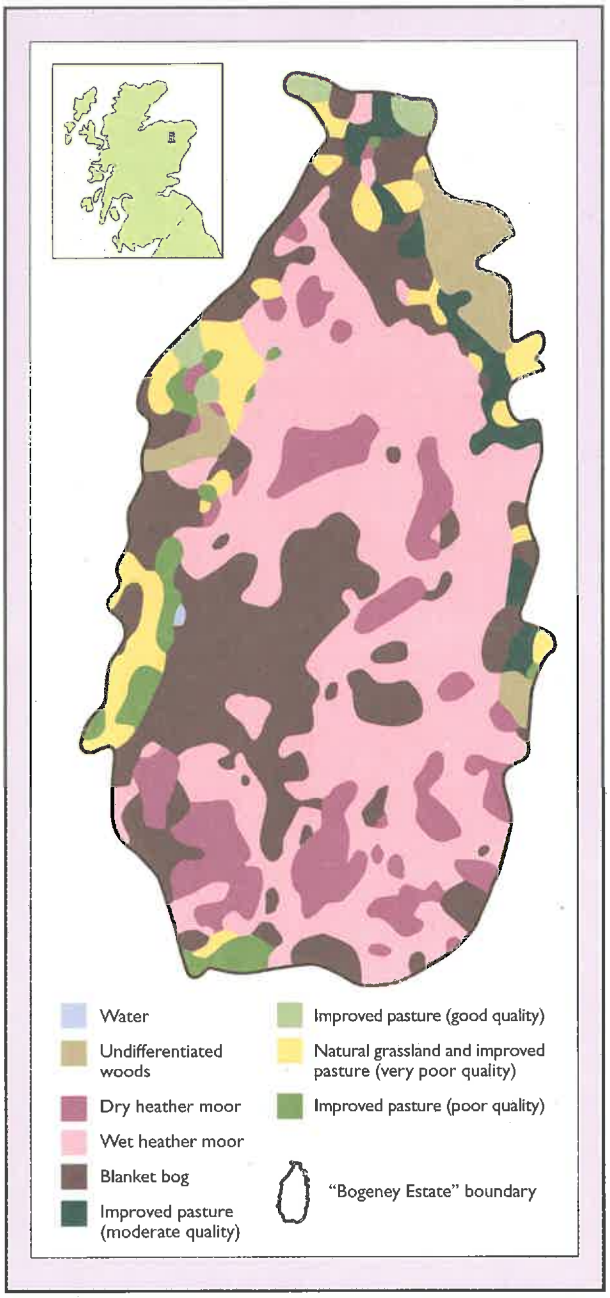

Figure 3. General location and diagramatic representation of the satellite classification of vegetation covers derived from satellite data (smoothed with a 9 x 9 majority filter)

resources of large areas of Scotland. Information on land cover, red deer and sheep numbers, topography and aspect, and soils, together with the use of impact models, such as HILLDEER (see page 90), are being used to identify areas which require to be sampled on the ground to give an accurate assessment of change with minimum inputs of ground survey data. The Cairngorm/Speyside, South Tayside and Gairloch areas of Scotland are being used to test the approach. This research in conjunction with Biomathemetics and Statistics Scotland will provide a new methodology which will have application to other situations. For example, one possible application is in assessing the impact of reindeer migrations on habitats in Sweden. The advantage of developing such methodologies in Scotland is that the data-rich nature of the information available provides an excellent test-bed for such studies.

The proactive role that the UK has taken in land use and land cover change measurement has given rise to a range of datasets designed to meet specific purposes, for example, the Department of the Environment, Transport and the Regions/Institute of Terrestrial Ecology Countryside Surveys, the Scottish Office Land Cover of Scotland, 1988 and Scottish Natural Heritage's National Countryside Monitoring System. The potential to link together such data sets based on census and sampling approaches, the development of robust change detection methods and the provision of flexibility in their use, are key research topics and have been identified as internationally important (Turner *et al.*, 1995). In conjunction with the Institute of Terrestrial Ecology progress has been made in integrating the different approaches and classification systems (Wyatt *et al.*, 1994; Brooker, 1995). The challenge for the future is in the development of more flexible of an interchangeable systems to meet the perceived information needs of an increasing and diverse range of customers. New technologies in the area of imaging (e.g., high resolution satellite imagery and digital aerial photography), data capture (e.g., on-screen digitising) and automated change detection methods (e.g., MLURI's SYMOLAC, an expert system for monitoring land cover change from a time-series of images; Skelsey, 1997) are being developed to meet these needs. Specifically, current research at MLURI is exploring methodologies of digital photography, on-screen digitising and automated land use change detection which will not only have value in a Scottish context but also internationally.

The role of modelling in enabling the prediction of the impact of land use change on biodiversity is central to the focus of several international initiatives of the International Geosphere-Biosphere Programme . The emphasis is changing towards predicting the impacts at smaller scales where the major drivers of change often operate and are susceptible to alteration by policy interventions. Collaborative research, building on previous work at MLURI using spatial modelling techniques (Dennis *et al.*, 1997), with the University of Glasgow and the Scottish Agricultural College will investigate the scaling-up of site-based models to the catchment scale for the prediction of the change in the biodiversity of a number of key biota associated with farmland.

A key issue, identified by a recent Electronic Conference on Land Use and Land Cover Change, was the need for inter-disciplinary research to allow better integration of the biophysical (environmental) and human dimensions of change (Lambin, 1997). It highlighted that there are very few examples of research that have addressed specific issues in this context. MLURI is making a contribution by tackling a problem which has not been addressed to date. Research on optimal designs for environmental monitoring has not considered comprehensively the cost-benefit issues involved. An economic appraisal methodology will be developed and a cost-effectiveness model applied to three contrasting environmental monitoring situations, viz countryside change, water quality and protected area management. This study will bring together researchers from a range of disciplines including environmental and socio-economics, ecology and hydrochemistry.

Relevance to End Users

Research focusing on the measurement of change is of high value to all those involved at regional, national governmental and international levels in policy formulation and implementation. Whilst most of the research at MLURI is pursued within a Scottish context and will be valuable to public bodies in Scotland, the research approaches, and the principles on which they are based, are relevant to and also applicable in an international context. The work, commissioned by the Scottish Office and its agencies to aid policy development and monitoring, e.g., the projects on land cover change detection, rapid habitat assessment and biodiversity modelling of agricultural land use change, represent exciting research challenges. Our research will continue to develop to meet such challenges at an internationally competitive level, in order to support and improve UK and European environmental and land use policy development.

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The management of land requires the integration of often complex ideas, the use of large quantities of data and the prediction of outcomes over a large number of years. For these reasons computer-based decision support tools offer a powerful medium for exploring land management issues.

Development of Decision Support Systems

Computer-based Decision Support Tools (DSTs) have the potential to become important tools for technology transfer. The UK has always invested heavily in Information Technology (IT) and has one of the highest IT growth rates in Europe. Around 75% of its large manufacturing companies have resource planning systems and the extension of these into land management has considerable potential. The use of IT is becoming more pervasive and land managers, policy advisers and consultants are now more receptive to the use of IT.

The management of land requires the integration of often complex ideas, the use of large quantities of data and the prediction of outcomes over a large number of years. The spatial distribution of different land uses, as influenced by climate, topography, soils, vegetation and the impacts of animals, the spatial nature of land holdings and administrative boundaries, the slow changes that occur in many circumstances and the large number of potential options, all lead to the conclusion that computer-based DSTs offer a powerful medium for exploring land management issues. Advances in computer languages and programme design, increases in computing power and more sophisticated means of displaying information are technical reasons why the time is ripe for developments in this area.

The multiple-objective nature of land use decision-making in the UK has meant that a range of government departments, government and non-government agencies and land managers have an increased requirement for more sophisticated tools for policy formulation and implementation. Computer-based DSTs can meet this need. DSTs can also be of value in education and teaching. All of these potential developments were recognised by the UK Government's Technology Foresight Steering Committee who identified that computer-based modelling, simulation studies, predictions from complex systems and information management were key research priorities.

Strategic Objectives

Although there are a vast number of applications for DSTs in land use management, there are a number of common features of DSTs that require to be developed to effectively realise their potential. Many of these have a generic application. Examples include user interfaces, databases, underlying model structures and derived data sets appropriate for a number of applications. For the DST applications currently being produced within the Institute's research programme on waste management, water quality prediction, impacts of large herbivores on biodiversity management, and land allocation options at the farm and regional scale, there are many common development objectives which have the potential to improve the quality and the efficiency with which DSTs can be produced.

To facilitate the achievement of these objectives the strategic aims of the research programme over the next five years are to:

- Facilitate the availability of basic data sets for use in decision support system developments.
- Develop appropriate data and model standards.
- Design systems which allow the interchangeability of sub-models.
- Design generic user interfaces to meet the needs of the user community.
- Develop derived data sets appropriate for a wide range of applications.

These objectives will be met through two strategic projects that are described below. These projects aim to underpin concomitant development of a number of DSTs to meet the technology transfer needs of programmes within all the research themes of the Institute, *viz:* Atmospheric Deposition, Land Use and Water Quality Management (PU23), Soil Quality, Contaminated Land and Waste Utilisation (PU24), Geographical and Resource Analysis (PU21) and Land Use Options for Animals (PU29). The production of these DSTs will ensure that the context of these strategic projects is kept under continual review.

Current Research

To facilitate the development of DSTs in the land management area a key feature is the easy accessibility to and use of data sets. The Data Resource and User Interface Development (DRUID) project, which is of 3 year's duration, involves the development of a meta-data information facility, a database holding both spatial and aspatial data and a user interface. The Institute owns and leases a number of data sets describing the land resources of Scotland which are essential for those working in research on land use and for the development of DST. These include those on soils at a number of scales, the Land Cover of Scotland 1988 data set, information on administrative boundaries, agricultural census statistics, climate and topography. A User's Group was set up at the start of the project and contributes to the development of DRUID through the use of structured interviews and feedback on releases of the user interface. The core of the meta-data information concerns the quality standard of the data. In collaboration with the Environmental Systems Research Institute (ESRI) a new system for handling spatial data, called the Spatial Data Engine, is being used for holding and manipulating spatial data, and in interfacing, using a technology being developed for the World Wide Web. To create an on-line service using spatial data the Arcview Internet Map Server is being used. DRUID will provide a unique integrated data set for use by those developing DSTs in relation to Scotland's land resources and will be of wider value to those undertaking research on a wide range of land resource issues. It has been designed in such a way that it will be easy to incorporate new data sets and data sets derived from those contained within DRUID.

In an analogous manner to the DRUID project on data sets, a project has been initiated to develop an Integrated Modelling Infrastructure for Land Use Research (IMILUR) to incorporate models of biophysical processes at a range of geographical scales. This involves research into designing standards for the development and description of land use-based models and the creation of a formal description language for models. The latter will be sufficiently rich to allow the development of a prototype interface to enable the models to be used together in DSTs.

Three prototype DSTs applications have been built in the past year to provide tools for use by the environmental agencies in Scotland. An integrated terrestrial aquatic spatial decision support system has been developed which holds past and current spatial and attribute information on the physical and chemical characteristics of Scottish lochs and their catchments. It interprets how nutrient status, in particular phosphorus status, will change over time (McAlister and Ferrier, in press). A second prototype has been built to assist in the management of biodiversity in upland landscapes. It predicts species assemblages of some insect taxa in relation to geographical location, land cover characteristics and grazing management (P Dennis unpublished). The third DST predicts appropriate woodland communities for areas of land by combining spatially based information on soils, land cover, topography and exposure. All of these DSTs use spatially arranged data combined with modelling.

A further two DSTs, entitled HILLPLAN and HILLDEER, designed for the Scottish Office Agriculture, Environment and Fisheries Department and the Deer Commission for Scotland respectively, predict the impact of large herbivores on the productivity and dynamics of upland vegetation and animal productivity, and in the case of HILLDEER, population dynamics. They have the same overall structure, are non-spatial, are individual animal-based and contain similar foraging and vegetation dynamics sub-models. They are written in C++ and use a similar user interface design and operating system. HILLDEER has been completed (Gordon and Hope, in press) and is described briefly below.

HILLDEER

- Designed for use by the Deer Commission for Scotland and the Association of Deer Management Groups.
- Combines a habitat impact model with a population dynamics model, designed by Biomathematics and Statistics for Scotland.
- Developed in conjunction with a user and expert group, including staff of Scottish Natural Heritage, the Institute of Terrestrial Ecology and the Game Conservancy.
- Tested with the help of a number of Deer Management Groups.
- Runs on PCs under the Windows 95© operating system.
- Launched in February 1998 with training given to Deer Commission for Scotland staff.

DSTs in land management

A historical perspective on how DSTs have evolved in the land management area over the last 15 years can be gained by reference to the development of the DST to aid the management of upland plant communities (now HILLPLAN). A model, written in FORTRAN, that was originally designed as a research tool to explore the significance of the ratio of improved pasture to heather moorland in influencing sheep productivity (Sibbald *et al.*, 1987), was used as the basis of a DST for informing farmers about the role of reseeded pasture and heather burning management. This DST was then used by Government Agencies to reach management agreements with farmers about stocking rates of sheep to achieve conservation objectives. This sequence was analogous to the development of other DSTs in agriculture taking place at the same time in the UK. Research applications were providing the springboard for the development of DSTs which were then used by extension agencies to aid them in giving advice to their clients (see papers in Hillyer *et al.*, 1981). They proved to be valuable in least-cost ration formulation, fertiliser application rates to crops and in dairy cow management but many research applications remained unused.

A second generation of DSTs appeared in the early 1990's, in particular in the USA and Australia. These were more specifically designed to meet the needs of extension workers in agriculture and farmers, although their design was still mainly in the hands of scientists. It is worth noting that this often led to a mismatch between the needs of users and the perception of their needs by scientists. Nevertheless, more helpful graphical user interfaces were developed and there were a number of examples of DSTs in land management, employing Geographical Information System displays of results (see papers in Agricultural Systems and Information Technology in 1992). Other DSTs were of high quality but were hampered in their uptake because of the reticence of the sector of the industry for which they were designed, for example GrazPlan (Donnelly *et al.*, 1997; Freer *et al.*, 1997). One of the problems of more widely used DSTs was that the financial support for developing upgrades to incorporate new modules of interest was difficult to obtain. In the UK, in particular, there was a dearth of second generation DSTs for land management.

One of the exceptions to this was the Hill Grazing Management Model developed by MLURI (Armstrong *et al.*, 1996; Armstrong *et al.*, 1996). This was a development of the first version referred to earlier (Sibbald *et al.*, 1987) and predicted the effect of sheep grazing on the utilisation rate of upland plant communities in the UK. It was designed to produce output that could be interpreted by ecologists and consultants, acting for government and non-government agencies, to predict the environmental impact of sheep grazing. It built on the success of the first version and since its launch in 1993 has been

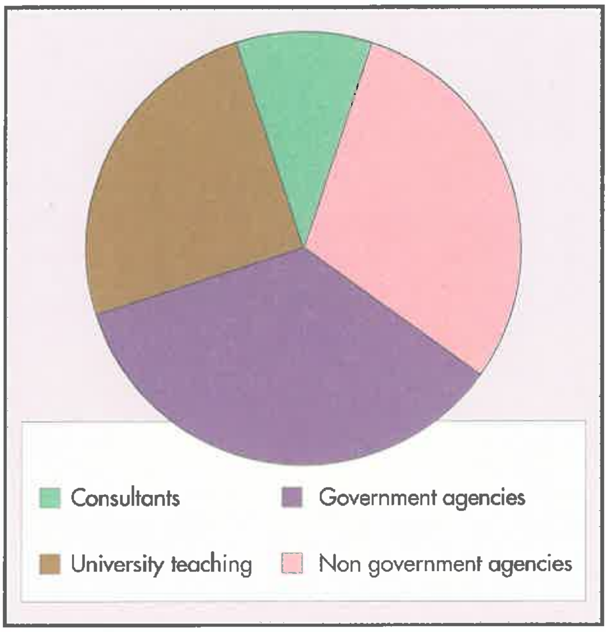

Figure 1. Clients for hill grazing management model.

widely used in the UK, both in policy implementation and consultancy but also in education (Figure 1).

In the 1990s, DSTs in the land management area have moved into a further stage of development. There have been a number of reasons for this. In part it has been driven by the pervasiveness of IT and the desire of governments to ensure that the results of research are applied and fully utilised. Technical developments also have played their part. Developments in Geographical Information Systems now make it easier to incorporate spatial data which are important in land management DSTs. Object-oriented programming has made it easier to develop the underlying models, and to make them easier to adapt and to reuse. Graphical User Interfaces are easier to develop and are of a much higher quality. Moreover, software design paradigms have developed such that they have been able to be readily incorporated into the production of DSTs.

This progress can be illustrated through reference to HILLPLAN. It arose from demands by users to increase the number of upland grazing management issues that could be explored in the Hill Grazing Management Model. HILLPLAN is designed to operate at the farm and/or estate scale and predicts the impact of sheep, cattle and deer grazing on the productivity and dynamics of upland vegetation. It is also designed to predict the productivity of sheep flocks and cattle herds and to deal with the movements of animals between land management areas (fields) and events that are specific to individual farms. The diagrammatic representation of HILLPLAN is given in Figure 2 (overleaf), to show the generic design elements that it contains. HILLPLAN follows what is becoming a classical software design for DSTs with the models containing the biological relationships held in the kernel which communicates through a wrapper system and a database interpreter

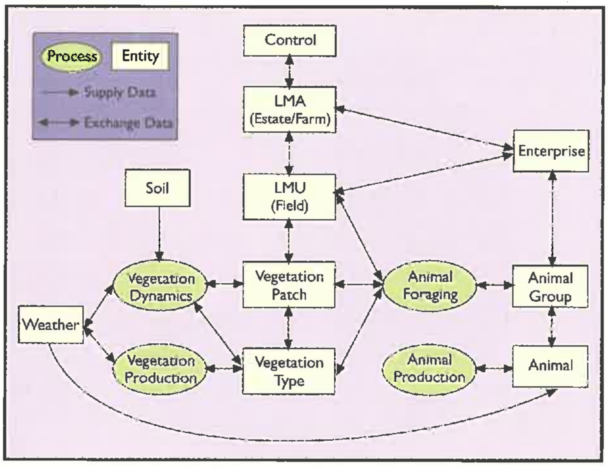

Figure 2. Modular Diagrammatic Representation of HILLPLAN.

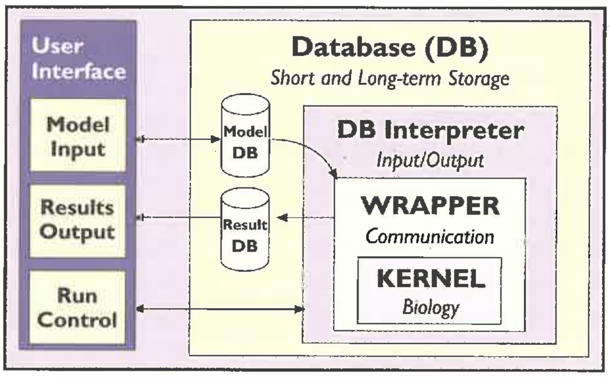

Figure 3. General structure of a decision support tool.

with the databases and the user interface (Figure 3). The current user interface has been designed with the involvement of users to ensure that it meets their needs. A team approach with up to seven staff working on the development of HILLPLAN has been adopted: a similar approach to that used by commercial software houses to develop small software packages.

HILLPLAN is the only DST that explores, for European temperate grassland and rangelands, the relationship between domestic animal numbers and their grazing habitat. It complements others which have been developed for the semi-arid rangelands of Australia and the United States and which are being used in the Global Change in Terrestrial Ecosystems project as part of the International Geosphere-Biosphere Program (Stafford Smith *et al.*, 1996; Campbell and Stafford Smith, 1998). Such DSTs have a role not only at the individual management unit level. They have also a role in the exploration of the regional impact of changes in animal numbers on environmental impacts and economic sustainability which is valuable in considering the implications of global land use cover change (Milne *et al.*, 1998).

There are a number of other DSTs under development in the UK in relation to crop management (e.g., DESSAC, Silsoe Research Institute, UK) and environmental management (Lewis *et al.*, 1996). They use some elements of Geographical Information Systems within them, allied to databases and deterministic and expert system - based models in an analogous manner to that described for the other DSTs which are being produced currently at MLURI. The lack of suitable means for combining models and databases makes it difficult for collaboration between groups to develop easily. However, the Integrated Modelling Infrastructure for Land Use Research project (IMILUR) should assist in achieving this in the future.

Future Developments

The completion of the first phase of the DRUID project will provide an unique resource to the scientists of the Macaulay Land Use Research Institute and will facilitate the development of future DSTs. The experience gained in developing a state-of -the-art land use database will also be valuable to other land use research organisations embarking on setting up or revising their data resources. The IMILUR project will provide an unique infrastructure whereby integration of biogeophysico-chemical models describing the processes involved in land management can be achieved. This will increase the flexibility and efficiency with which DSTs can be produced.

There are a number of applications which will lead to the further development of DSTs designed to aid management of the vegetation of the uplands of the UK (Milne, 1997). For example, by linking elements of HILLDEER with the DST on Native Woodland Restoration it will be possible to create a new DST, tentatively named WOODDEER. This will predict the impact of deer browsing native woodland on regeneration and tree damage, and the effect of access to woodland on the performance of deer. HILLPLAN will be developed also to meet the wider needs of an extended range of users.

New initiatives in developing DSTs for environmental management, for example in relation to the disposal of wastes on land, will be considerably aided by the successful outcomes of the DRUID and IMILUR projects. In all these developments increasing emphasis will be given to identifying the current and future needs and the involvement of users in the construction of DSTs.

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ANALYTICAL GROUP

The chemical and physical analytical facilities within the Analytical Group have been used extensively in support of the research programme of the Institute. The changing nature of the research programme has necessitated that the analytical facilities be expanded to incorporate new techniques and procedures which relate mainly to the measurement of physical characteristics of soil. The number of samples submitted by the Research Groups for analyses was of the order of 100K and the total number of analytes determined, totalled 1500K. To enable the analysis of such a large number of samples, a heavy emphasis is placed on the use of computer technology to allocate work, monitor sample analysis progress and report results. The production of analytical data has been streamlined by the introduction of computer readable barcodes for sample identification and of in-house software programmes and computer spreadsheets.

Analyses are carried out on soils, waters and plant and biological material. Extensive use is made of inductively coupled plasma-optical emission spectroscopy (ICP-OES) and graphite furnace atomic absorption spectrophotometry for inorganic element analyses. Facilities are also available for the determination of both heavy and light stable isotopes using mass spectrometry. Heavy isotopes of inorganic elements such as lead, cadmium, nickel, copper, zinc and strontium are determined by the highly precise technique of thermal ionisation mass spectrometry (TIMS) while the light isotopes of hydrogen, carbon, nitrogen and oxygen are measured using continuous flow and static mass spectrometry. Gas chromatography linked to mass spectrometry is used to determine the stable isotopic content of nitrogen in intact molecules such as amino acids.

There is a substantial requirement for the analyses of waters for a wide range of analytes. Anions such as chloride, nitrate and sulphate are determined by ion suppressed chromatography whereas the techniques of segmented flow and flow injection analysis are used to estimate ammonium ion, soluble reactive phosphate, nitrite and alkalinity. The content of inorganic and organic carbon in waters is measured by non-dispersive infra-red spectroscopy.

The demands of the research programme necessitates that soils and plant and biological materials are analysed for organic compounds included among which are n-alkanes, alcohols, esters, carbohydrates, amino acids and fatty acids. The analyses of such compounds are effected by gas chromatography alone or linked to mass spectrometry. Recently, methods have been developed to allow the estimation of fatty acids in phospholipids in soil microbial populations.

Automated gas chromatographic analysis

Isotope ratio mass spectrometry

Determination of radioisotopes

To enable analyses to be carried out in a cost effective manner, instruments which are designed for a high throughput of work are fitted with autosamplers so that staff involvement is reduced to a minimum. The large amount of data generated is handled by making extensive use of software programmes to allow calculations to be made and quality control of the results to be maintained. Further, all work submitted to the Group is monitored through the use of an information management system which also provides financial information to the Research Groups for the samples submitted for analysis. As far as possible, there is a policy within the Group to use modern automated equipment and data handling facilities so that staff involvement in the routine aspects of providing analytical data is reduced to a minimum. Staff time can then be used more effectively in developing new procedures and systems to increase the efficiency of the service.

Although the bulk of the work undertaken by the Group is effected through automated techniques, there is also a requirement for analyses to be carried out on a manual basis. These relate mainly to the systematic analysis of soils, including the measurement of physical characteristics, and to the analyses of animal feeding stuffs for fibre type and content, digestibility and carbohydrate content. Methods which allow the estimation of these parameters using automation have not yet been developed to a stage where they can be used on an extensive basis.

The Group operates a formal quality assurance scheme which guarantees the quality of data. The scheme is based on the standards laid down for chemical testing by the United Kingdom Accreditation Service (UKAS) and the work of the laboratories has been assessed by UKAS. The award of accreditation is imminent.

Service Level Agreement

The delivery of a service from the Analytical Group to the Research Groups is based on a Service Level Agreement. The Agreement is an undertaking to carry out a defined number and type of analyses for an agreed cost within any one financial year. Deadlines for the delivery of the service are agreed with Research Objective Leaders and if these are not met a written explanation is made to Programme Unit Managers. The Agreement includes a commitment to operate to formal quality control standards and to participate in proficiency tests so that the performance of the laboratories can be compared with that of others. There is also a complaints procedure built into the Agreement so that any disagreement or dissatisfaction of the service can be identified and resolved.

Segmented flow analysis

Measurement of total carbon

Inductively coupled plasma-optical emission spectroscopy

ANALYTICAL GROUP

Commercialisation

There has been a continued expansion of commercial work which requires the use of the extensive suite of analytical facilities. A broad range of work is undertaken with particular emphasis on providing specialist analytical information to commercial companies who require solutions to specific operational problems. The techniques most used to service commercial work include X-ray diffraction, infra-red spectroscopy, electron microscopy and gas chromatography linked to mass spectrometry. The advantage of being able to add value to the product which is offered through an ability to interpret analytical data has proven to be a major selling point to commercial customers. It has been identified that the oil service sector is an area from which increased business can be obtained and an emphasis is being made to market our expertise to that sector.

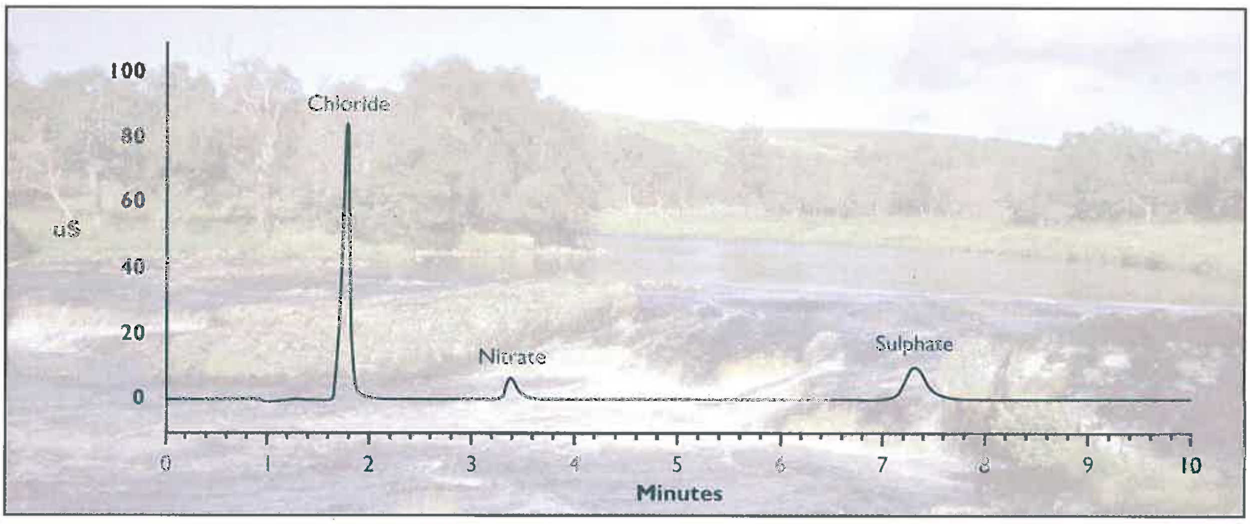
The customer base has continued to expand with an increasing amount of income being derived from oil related business. Other areas from which income from analytical work is derived include agriculture and horticulture, product manufacturing, engineering and alcohol distilling. Work is also carried out for public funded organisations and for companies which require development of analytical methods.

Strategic Development

Although the work of the Analytical Group is defined by the analytical requirements of the Research Groups, there is a clear need to continue to develop a strategy which allows the research programme to be serviced in an efficient manner. Over the next few years, attention will be focused on identification and evaluation of instrumentation which will eliminate the requirement for certain analyses to be undertaken on a manual basis. The predictive technique of near infra-red reflectance may be suitable for determining fibre and digestibility content of the diverse range of plant species under study. The determination of soil physical characteristics such as particle size distribution can be determined to a greater degree of definition and resolution by the use of laser technology. An assessment needs to be made of such technology to ascertain if it can be applied or adapted to meet the research programme requirements.

To decrease the unit cost of analysis, equipment which can perform in multi-functional mode is essential and the feasibility is being investigated of using ICP linked to mass spectrometry (ICP-MS) to determine isotope ratios of inorganic elements and to obtain greater levels of sensitivity for the detection of trace elements than can be obtained by ICP-OES. Such an option is particularly attractive in that the cost of ICP-MS equipment is considerably less than that of a TIMS instrument which is currently used to determine isotope ratios.

At all times, the strategy of the Group is to identify and introduce cost effective analytical facilities while at the same time maintaining high quality output.



Chromatogram of typical Scottish river water anion content

COMPUTING AND INFORMATION SERVICES

Much of the work of the Institute requires the use of large spatially-distributed datasets, and the computing resources to hold and manipulate them efficiently. There is a related need to be able to present the results of research, often involving complex maps and diagrams, in an effective and easily understood form. There is an increasing need for high speed access to the international data network and for use of information-retrieval services such as the Web.

The Computing and Information Services Group provides a range of services within the Institute, to address these needs.

It comprises two sections:

- Computing
- Library

In addition, the Head of Group is the Training Officer and Post-Graduate Student Liaison Officer.

Services Provided

Computing

The Computing Section maintains and develops the Institute's core computing and network infrastructure.

A key aspect of the Institute's computing needs is fast, efficient access to computational, data and information resources on the global data network. MLURI has a fast, efficient Local Area Network with access from every office and work area. This is connected to a high-bandwidth Metropolitan Area Network, linking the Universities and Research Institutes in Aberdeen, and thence to the UK Academic Network, and the International Network.

Increasingly, the World Wide Web is an important medium for information retrieval and technology transfer. The rapid growth of this facility has placed additional demands on the capacity of the data networks at all levels. The Institute uses its own Web site both for making information accessible to the outside world, as well as for distributing information within the Institute.

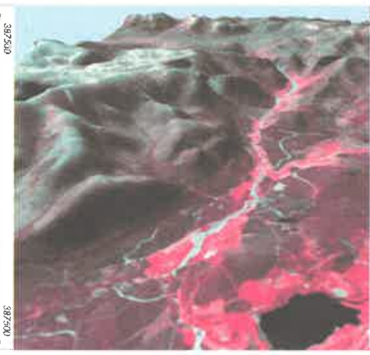
The Computing Support section provides the following Services:

- Management and development of the Local Area Network, data communications links with MLURI's research farms, and the link to the external network.
- A basic, general-purpose computer service, based on UNIX work-stations.
- Management of site access and data security measures, including protection against unauthorised access, anti-virus measures and data backup.

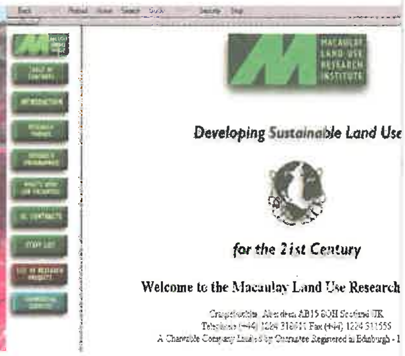
Computing applications

Landscape visualisation: Glens of Foudland, a prospective wind farm, July 2000?

Unique data sets: Distribution of Land Cover types at Sourhope Farm



Satellite imagery: Glen Feshie, Landsat Thematic Mapper, June 1995



http://www.mluri.sari.ac.uk

- Management and development of an ORACLE Relational Database Management System (RDBMS), with client-server access from PCs and UNIX work-stations.
- Data entry, data manipulation and reporting for research and administrative requirements, based on the ORACLE RDBMS.
- Development of ORACLE applications for research and administrative needs.
- A support service, for users of PC and UNIX platforms. This service covers assistance with purchase of hardware and software, resolution of problems associated with the core facilities provided by CIS, and general assistance with computing problems and issues.
- Management of Institute information accessible via World-Wide-Web facilities.

Library

The role of the library is changing, as new network-based information sources become increasingly important. A growing number of on-line information sources are now available. An important part of the library's function is the management of access to these facilities.

The library provides a comprehensive range of traditional services, combined with access to on-line information sources.

It offers the following services:

- Management of the Institute's book, periodicals and staff publications resource, including cataloguing and loans management.
- Purchase of new books and periodicals.
- Inter-library loans.
- On-line searches of external databases.
- Management of the computer-based open-learning facility.

Training

The Institute arranges for training for staff as needed, in a wide range of areas: personal, technical and further education. Training is mostly carried out by professional trainers from outwith the Institute. Where appropriate, staff are supported in carrying out undergraduate or post-graduate studies, part-time. The Institute houses full-time MSc and PhD students during part or all of their course.

Recent Developments

The computing infrastructure and support services provided by CIS has been expanded in two important areas:

- The bandwidth of the Local Area Network has been greatly expanded through the implementation of a set of high-speed switches

Library

A quiet place to study

All the latest journals

Open-learning facility

and optical fibre backbone. The net effect has been to raise the capacity by an order of magnitude.

- The computing support service staffing level has been increased, to enable more efficient handling of maintenance and development of the infrastructure, whilst improving the support service for users. This has also enabled detailed statistics to be collected to establish the effectiveness of the service, and enable further improvements to be made within the context of a Service Level Agreement.

Future Developments

The current focus is on improving the robustness of the computing infrastructure, in the event of break-downs. The increasing dependence of nearly all aspects of work on the computing facilities, has brought this recently to a much higher priority than ever before. This involves a number of measures, such as the implementation of matched processors, able to take on each others tasks, redundancy in data-storage facilities and clearly identifying critical applications.

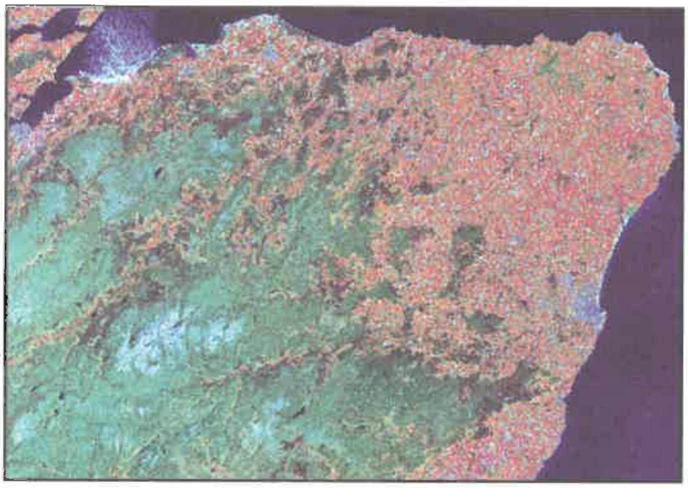
A number of trends can be discerned in hardware and software, which are likely to influence our future procurement decisions. The integration of real-time voice and video transmission into the data network will facilitate long-distance collaboration. The development of more powerful Web search engines of all kinds, including roving, intelligent 'agents' will powerfully boost the ability of researchers to acquire information. However, this will also increase the pressure on security measures to gain access to our computers. There will be a need to continually refine these measures. Finally, the rapid growth of computer storage capacities and communication bandwidth, both for the LAN, and external networks, will continue. Data back-up and archiving facilities will need to change accordingly. At the same time, 'thin-client' hardware and software (i.e. graphics terminal on desk, processing power in central server) will become increasingly more attractive for a range of users, than having a PC on each desk – reducing lifetime costs and increasing robustness.

Service Level Agreement

This document defines the level of service offered by CIS Group, in each of the services described above. It is formally an agreement between the Head of CIS Group, and the Heads of the other Groups within the Institute. The parameters describing level of service vary according to the nature of the service. For basic infrastructure, the parameters include degree of continuity of service and capacity. For user support functions, the parameters include speed of response and time-to-complete. Comprehensive statistics are maintained, and reported to Heads of Group on a monthly basis.

Computing Code of Conduct

This document specifies acceptable and unacceptable use of Institute computing facilities. It is based on a document produced by BBSRC, modified to suit local conditions.



North-East Scotland extract from a geometrically corrected Landsat TM image (26/6/95, false colour composite)

MACAULAY RESEARCH & CONSULTANCY SERVICES

Specialist Services for the Land Manager

Macaulay Research and Consultancy Services was established in 1994 as the commercial arm of MLURI. MRCS has full access to the staff and facilities of the parent organisation and so is able to provide a wide range of specialist research and consultancy services for the land manager.

A substantial part of MRCS business is concerned with natural heritage and environmental management. This expertise stems from the international reputation for research on grazing ecology enjoyed by the Macaulay Institute. This expertise, in particular, is opening up the overseas market for MRCS with projects in Pakistan, Central Asia and Southern Africa underway.

Research and consultancy on the investigation, assessment and stability of contaminated sites is another important sector of MRCS business. The work undertaken ranges from simple site assessments, largely involving analytical and land consultancy expertise, through to more sophisticated investigative techniques which can be linked to computer modelling to provide information on the stability of contaminated sites.

MRCS services in this area for both metal and organic contaminants are in demand from a wide customer base both national and international.

Another key service available for environmental managers is research and consultancy expertise on the utilisation of organic wastes on land. This ranges from strategic advice on land suitability for the acceptance of wastes to undertaking research aimed at mechanistic understanding of the long-term impacts on soil and water quality.

A commercial analytical service is also available which has a wide customer base from many sectors of industry including those related to oil, water, agriculture, horticulture and engineering.

The symbiotic relationship between MLURI and MRCS continues to be a major competitive strength for the business and in 1998 we look forward to new consultancy opportunities arising from specialist decision-support tools being developed for the land manager.

Discussing the use of natural resources with villagers in the northern area of Pakistan

Mapping heather moorland on Islay

Peat sampling

The range of MRCS products and services includes:

- **Soils and water environmental management**
  - Water quality and catchment management
  - Impacts of air pollution on terrestrial and aquatic ecosystems
  - Management and utilisation of organic wastes on land
  - Investigation and assessment of stability of contaminated sites

- **Natural heritage management**
  - Soil, peat and vegetation surveys and habitat assessments
  - Rangeland management

- **Sustainable rural land use**
  - Development and management of marginal lands
  - Development of forestry, farm woodlands and agroforestry systems
  - Land capability assessments
  - Strategic land use planning
  - Environmental and socio-economic impacts of land use

- **Data services and products**
  - Data leasing from MLURI's unique environmental datasets
  - Data capture and GIS services
  - Tailor-made environmental data products

- **Analytical services**
  - Wide range of analyses for environmental and rural industry markets
  - Characterisation of inorganic and organic compounds for oil related sectors
  - Method development and trouble shooting
  - Competitive prices
  - Fast turn around time

For further information on MRCS business please contact the External Affairs Officer.

Distillery waste treatment

Assessing a contaminated site

State of the art analytical facilities

BioSS

Biomathematics and Statistics Scotland

Biomathematics and Statistics Scotland (BioSS) contributes research, consultancy and training in statistics and mathematics to agricultural and biological organisations in Scotland. Its 30 graduate staff are based at BioSS Headquarters in the University of Edinburgh and in units in Aberdeen (at both MLURI and Rowett Research Institute), Dundee (at Scottish Crops Research Institute), and Ayr (Hannah Research Institute).

BioSS has particular expertise in the areas of Environmental Modelling, Image Analysis, Mathematical and Systems Modelling, Molecular Biology, Plant Breeding and Variety Testing, and Food and Nutrition. Major projects in these areas call on the services of the relevant BioSS specialists.

During 1997, there have been 9 BioSS posts in Aberdeen, 5 of which were based in the Environmental Modelling Unit at MLURI. The primary duties of the Unit are:

- To provide a consultancy service to MLURI scientists.
- To engage in collaborative research with scientists from MLURI and elsewhere.
- To develop programmes of applied statistical research.
- To undertake related contract work.

The consultancy service is operated through an open door policy whereby a member of staff is available each afternoon of the week. In total, BioSS staff have had meetings with 90 scientists, visiting workers and research students during the year. Topics covered include: experimental design; data analysis and regression modelling; statistical computing; interpretation of results; and the presentation of methods and results in scientific papers.

Collaborative projects arise out of contacts initiated through the consultancy service, and lead to joint publications with MLURI and BioSS co-authors. Some current examples of such collaborations with staff in the different MLURI Groups are as follows.

- Valuation of environmental goods by analysis of preferences expressed in questionnaire surveys.
- Identification of grass roots from the

Output from the decision support tool HILLDEER: Predicted numbers of red deer with 75% confidence intervals

concentrations of alkanes, and estimation of proportions of each species in a mixture.

- Estimation of correlations between animals in experiments where treatments are applied to groups, to achieve analyses which are both valid and efficient.

- Detection of long-term trends in water chemistry, after the removal of noise due to seasonal effects and variations in stream flow.

BioSS and MLURI have jointly developed HILLDEER, a user-friendly Decision Support System for management of Red Deer on the open hill in Scotland. HILLDEER contains a population dynamics model produced by BioSS which uses simulated Bayesian inference to integrate prior knowledge about closely studied deer populations with counts and cull data from any Deer Management Group area. Use of HILLDEER ensures management decisions are based on the best available estimates of their likely consequences.

BioSS provides training to scientists, both formally through computer-based short courses in Statistics and Mathematical Modelling, and also informally through discussions with individuals and small groups. This training raises the level of statistical awareness and abilities amongst scientists, allowing the statistical consultants to spend a greater proportion of their time on those projects which require the use of advanced statistical methods. During 1997, MLURI staff attended 12 different BioSS courses and received a total of 78 person-days of training.

Additional income of the Unit comes from external sources. BioSS, MLURI and the Institute of Hydrology have recently completed a joint review for SOAEFD of the Harmonised Monitoring Scheme for collecting data on river chemistry in Scotland. A long-term contract involving BioSS, MLURI and ITE scientists is the monitoring the Scottish Environmentally Sensitive Areas. Another long-standing contract is for BioSS to provide statistical input to projects at ITE Banchory. Of particular interest this year has been the application of results from diffusion theory to the movement of radio-tracked animals.

Modelling of sulphate in streamwater (data × and fitted values —) to reveal trends in water quality (—)

ABERDEEN RESEARCH CONSORTIUM

MLURI is a participant in the Aberdeen Research Consortium.

The Aberdeen Research Consortium consists of three centres of research excellence in life and environmental sciences. Combining the strengths of two universities and seven scientific institutes, it serves industry, government, international agencies and the community in the UK, Europe and worldwide. The three research centres are:

- Aquatic Sciences Research Centre
- Boyd Orr Research Centre for Nutrition and Food Sciences
- Land Management and Environmental Sciences Research Centre

Land Management and Environmental Sciences Research Centre (LMESRC)

This Centre integrates soil, land, plant, animal and environmental sciences. It undertakes research to identify means whereby land and natural resources can be used to create wealth while preserving our natural heritage and the quality of life.

The members of the Centre are:

Institute of Terrestrial Ecology, Banchory
Macaulay Land Use Research Institute
The Robert Gordon University
The University of Aberdeen
Scottish Agricultural College, Aberdeen

The Centre aims to:

- Develop effective working relationships amongst its members by encouraging and facilitating joint programmes of research, offering competitive post-graduate research fellowships and enhancing research capability in specific areas of interest.
- Add value to the existing activities of member organisations by winning research and consultancy projects.
- Raise the awareness of the public, the sponsoring bodies and the international research community of ARC and LMESRC by organising workshops, symposia and international conferences on relevant topics.

The foci of research within the Centre include:

soil microbial ecology
pollution control and water management
land use economics
ecology of grazing systems
geographic information systems technology
sustainable land use systems

For further details please contact Professor P A Racey, Convener of LMESRC, Department of Zoology, University of Aberdeen, Tel: 01224 272858, Fax: 01224 272396, email: p.racey@abdn.ac.uk

ARC projects in which the Institute is involved/include:

Modelling vole populations at the landscape scale

The structuring of remote sensing and land cover knowledge for automated land cover change detection

Integrated system for analysing and reporting on the social, economic and environmental dimensions of rural land use change

Prediction of spatial and temporal variation in the solute chemistry of a major river system from the integration of models of terrestrial and hydrological processes

Assessment of the biological impact and remediation of oil contamination in soils

Interactions between N status and carbon partitioning on the development of *Vaccinium*

Quantify the role of species interactions during foraging on the functioning of mammalian communities

Urinary metabolites as markers of dietary intake in free ranging ruminants

The mechanistic basis of food selection by mountain hares and its importance on native woodland dynamics

Pre and post-natal development of the reproductive axis in intrauterine growth restricted lambs

Neuroendocrine control of appetite and reproduction in sheep

Critical loads of acidity to soil and surface waters in selected Scottish catchments

CHABOS

The Committee of Heads of Agricultural and Biological Organisations of Scotland

MLURI is a participating member of CHABOS

CHABOS (The Committee of Heads of Agricultural and Biological Organisations of Scotland) was formed in 1994 to promote an integrated approach to biological, environmental and agricultural research and development, technology transfer and policy support in Scotland. The member institutions embody intellectual enquiry, education, and the public appreciation of science.

The organisations represented on CHABOS include

Fisheries Research Services (FRS)
Forestry Commission Research Division (FCRD)
Hannah Research Institute (HRI)
Macaulay Land Use Research Institute (MLURI)
Moredun Research Institute (MRI)
Rowett Research Institute (RRI)
Royal Botanic Garden Edinburgh (RBGE)
Scottish Agricultural College (SAC)
Scottish Agricultural Science Agency (SASA)
Scottish Crop Research Institute (SCRI)

They are supported by Biomathematics and Statistics Scotland (BioSS) and offer a unique range of skills in microbial, plant and mammalian biochemistry and physiology, recombinant technology, aquaculture, animal and crop diseases, food technology, applied engineering, socio-economics, agricultural and land use systems, plant systematics and management of biological collections.

Objectives

- To develop co-ordinated and internationally competitive programmes of research in biological and environmental sciences.
- To capitalise on the scientific expertise within the member organisations, to nurture their creative and innovative talents, and to carry out research of the highest international quality.
- To promote technology transfer and contribute to technology foresight through continued interaction with industry and Government Departments.
- To provide advanced education and training in biological, environmental and agricultural sciences and cognate subjects.
- To advise and represent Government in S&T policy matters relating to agriculture, forestry, the environment and fisheries.
- To maintain monitoring programmes on disease prevalence in crops and animals and on environmental pollution.
- To promote the public appreciation of science and its contribution to national prosperity, health and well-being, and protection of the environment.
- To manage plant collections and promote their use in plant systematics.

For further information please contact the Convener, Professor P C Thomas, Principal and Chief Executive, Scottish Agricultural College, Central Office, West Mains Road, Edinburgh EH9 3JG, Tel: 0131 535 4001, Fax: 0131 535 4242, email: d.drummond@ed.sac.ac.uk

CHABOS projects in which the Institute is involved include:

Modelling environmental impacts of land use change

Automated land cover change detection

Predictive modelling of eutrophication within the river Ythan catchment and the development of an integrated management plan

Wastes to land-planning and design of a spatially based decision support tool

The herbivore's dilemma: Trade-offs between nutrition and parasitism in foraging decisions

Effects of pre-natal nutrition, colostral immuno-modulators and lamb growth factors on aspects of innate and adaptive immunity in lambs

Selection of goats for resistance to gastro-intestinal nematodes

Phenotypic and genotypic basis of population dynamics in heterogeneous species-rich grassland

Selecting for reduced aggression in pigs

Development and application of molecular biological techniques in studies of the interactions between microbes, nutrient cycling and vegetation among a range of agriculturally important pastures, to enable scale from microcosm to field

Modelling plant and animal biodiversity associated with a Scottish catchment devoted to agriculture

Aiding the application of HILLDEER by Deer Commission for Scotland and deer managers in Scotland

INSTITUTE STAFF

1 January 1998
[Group Structure as from 1/4/98]

DIRECTOR'S UNIT

Director

Professor T Jeff Maxwell, OBE, B.Sc., Ph.D., C.Biol., F.I.Biol, FRSGS, FRSE

Deputy Director

John A Milne, BA., B.Sc., Ph.D., FRSA

Assistant to the Director

Deborah J Slater, B.Sc., Ph.D.

Director's Unit Secretaries

Catherine M Smollet

Kathryn M Milne

External Affairs Officer

Sue P Bird, B.Sc., Ph.D.

Public Relations Assistant

Jane Lund, HND

Graphics Unit

Corrie A Bruce, HND
Patricia R Carnegie
David J Riley
Caroline C Milne

Staff who have left the Director's Unit since the last Annual Report

Heather A Fox
Claire L Howard, B.Sc., Ph.D.

LAND USE SCIENCE GROUP

Head of Group/Programme Unit Manager

Richard V Birnie, B.Sc., Ph.D., PGCE

Group Secretary

Lucy M Burnett

Research Objective Leaders

Alan R Sibbald
Gordon Hudson, B.Sc., GAeostat. (ENSMP Dipl.)
Alistair N R Law, MA, M.Sc., Ph.D., C.Phys., M.Inst.P.
David R Miller, B.Sc., Ph.D., RICS
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Allan Lilly, B.Sc., M.Sc., Ph.D.
Keith B Matthews, MA, M.Sc.
William Towers, B.Sc.
Matt P Hare, BA

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Andrew J I Dalziel, B.Sc.
Alistair Geddes B.Sc., M.Sc.
Kevin H Jones, B.Sc., M.Sc.
Alexander D Moir
Jane G Morrice, MA
J Gareth Polhill, BA., Ph.D.
Adrian R Taylor, B.Sc., M.Sc.
Roger A Dunham, B.Sc., Ph.D.
Paula L Horne, HNC
Julia A Mitchell, B.Sc.
David J Stone, B.Sc., M.Sc. FRMetS.
Susan MacLeay, B.Sc.
Ruth A Morrison, Dipl. Cart.

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Matt P Hare, BA

Staff who have left Land Use Science Group since the last Annual Report

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David T Bryant, BA

ENVIRONMENTAL AND SOCIO-ECONOMICS GROUP

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Consultant

Neil A Chalmers, B.Sc.

Staff who have left Environmental and Socio-Economics Group since the last Annual Report

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SOIL SCIENCE GROUP

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Edward Paterson, B.Sc., C.Chem., FRSC

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Group Secretary

Aileen Stewart

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Hans C L Meeussen, M.Sc., Ph.D.

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Lynn M Clark, LRSC
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Annette Kelly, HNC, BA
Caroline M Thomson, HNC
Kimberley A Wood, HNC
Clare M Cameron
Patricia Cooper
Sheila Gibbs
Frank W Milne
Angela Norrie
Malcolm C Coull, B.Sc.

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Electron Microscopy

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Staff who have left Soil Science Group since the last Annual Report

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Michael Thomson
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Elaine McAlister, B.Sc., M.Sc.

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Head of Group/Programme Unit Manager

Peter Millard, B.Sc., Ph.D.

Group Secretary

Iona M Shand

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Mike F Proe, B.Sc., Ph.D.
Charles A Shand, B.Sc., Ph.D.
Barry Thornton, B.Sc., Ph.D.
Pippa J Chapman, B.Sc., Ph.D.
Lorna A Dawson, B.Sc., Ph.D.

Other Staff

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ECOLOGY & ANIMAL SCIENCE GROUP

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Marjory A Wood

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Keely P Taylor

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Kathleen H Davidson

Radiochemistry

Terry Atkinson, LRSC (Consultant)

Colorimetric Analyses and Chromatography

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Donna MacDonald
Gillian Martin
Maureen M Procee, HNC
T Dawn Morley
Ann A Bruce

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Gordon W Stott

Cleaners

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Meg A Walker
Marjorie C Watt

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Brian N Kemp

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Doris M McCombie

COMPUTING & INFORMATION SERVICES GROUP

Head of Group

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Carol A Smith

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R Scott Boylan, B.Sc.
Helen M McGregor
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Jean A McGuiness, BLIB

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Patricia R Carnegie
David J Riley
Caroline C Milne

RESEARCH STATIONS GROUP

Head of Group

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GLENSAUGH (G)

Head

John A Milne, BA., B.Sc., Ph.D., FRSA

Farm Resources

Officer-in-Charge

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Administrative Assistant

Sheila M Humphries

Staff

John W Black (Snr) (Grieve)
Norman G McEwan (Head Shepherd)
John W Black (Jnr) (Tractorman)
James Scott (Shepherd)
June Scott (Cleaner)

Animal House

Officer-in-Charge

A Robson Fawcett, AIMLS

Staff

Andrew G Brown
A Craig MacEachern

HARTWOOD (H)

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George K D Corsar, B.Sc., MS

Typist

Catherine Walsh, HND

Staff

Ian Boustead (Grieve)
Robert Graham (Head Stockman-Cattle)
Jim C MacDonald, B.Sc. (Stockworker-Sheep Records)
Robert Armstrong (Stockworker)
Betty Farley (Cleaner)

SOURHOPE (S)

Officer-in-Charge

Harry M Sangster, B.Sc., Dip.FBom

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Geoffrey D Gittus, NDA (Deputy Officer-in-Charge)
John L Wallace (Head Shepherd)
Patricia Gentry (Recording Officer)
James C Pringle (Stockman/ Tractorman)
T Gavin Rogerson, Dip.FBom (Goats)
Pamela Tapson (Shepherd)
Matthew J Wilson (Shepherd)
Dorothy H Wallace (Cleaner)

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ADMINISTRATION GROUP

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Robert B Devine, DPA, MIMgt

Institute Deputy Secretary/ Finance Officer

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Graham A Thomson

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Christina M R Burness
Catherine B Adams
Janice M Laing
Jacqueline S Wales

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Lucy M Burnett
Iona M Shand
Aileen Stewart
Carol A Smith

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May L Watson

Stores

Lynne Thomson

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Ernest C Milne
David H Burgess
Allan E J Rhynas
Wilfred F Wallace

Cunningham Building Caretaker

Catherine Milne

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Staff who have left Macaulay Research and Consultancy Services since the last Annual Report

Victoria L Gilham, B.Sc., MA

BIOSS STAFF BASED AT MLURI

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Other Staff

David Hirst, B.Sc., Ph.D.
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Trevor S Smart, BA, M.Sc.

Staff who have left BioSS at MLURI since the last Annual Report

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HONORARY FELLOWS

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A M Ure, B.Sc., Ph.D., C.Chem., FRSC

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VISITING WORKERS

During 1997

LAND USE SCIENCE GROUP

Anna Ying-Ying Chung, The Chinese University of Hong Kong, Hong Kong.
Dr Yuanhua Dong, Institute of Soil Science, Chinese Academy of Sciences, China.

SOIL SCIENCE GROUP

Wendy van Beinum, Agricultural University Wageningen, The Netherlands.
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Natividad Galvez, Cordoba University, Spain.
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Dr Jouko Sippola, Agricultural Research Centre, Finland.
Keiko Suzuki, University of Aberdeen, Scotland.

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Christoph Neubauer, Westsächsische Hochschule Zwickau, Germany.
Dr Christophe Nguyen, INRA, France.
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Celine Sauvin, EPFL, Switzerland.
David Warren Stephen, University of Canterbury, New Zealand.

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Hinko Talsma, Wageningen Agricultural University, The Netherlands.
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Jia-En Sheu, University of Aberdeen, Self-funding
JoAnna Wherrett, Robert Gordon University, RGU/MLURI

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Patricia da Silva, University of Aberdeen, Aberdeen Research Consortium
David Villar, University of Aberdeen, Spanish Government

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Ahmed Ayoub, Robert Gordon University, Self-funding

PROGRAMME of RESEARCH

Current projects as of 1 April 1998

Research projects in Programme Units 21-38 are funded by SOAEFD

PROGRAMME UNIT 21

GEOGRAPHICAL AND RESOURCE ANALYSIS

Programme Unit Manager:
R V Birnie

121 371 Decision support systems for assessing land use options at the management unit level (K B Matthews)

121 401 Integration of land cover and agricultural information from the Agricultural and Horticultural Census of SOAFD with the Land Cover of Scotland 1988 (LCS88) to provide an enhanced, co-ordinated and multi-temporal Land Cover Database for Scotland (R V Birnie) [Flexible Funding]

121 440 Development of a generic methodology and physical environmental impact assessment (D R Miller)

121 453 The development of visualisation techniques for landscape evaluation (D R Miller) [Non-commissioned]

121 556 Development of efficient, biologically sustainable and economically viable upland sheep systems (A R Sibbald)

121 557 The role of spatially distributed interactions in integrated land-use systems (A R Sibbald)

121 558 Indicators of risk and resilience: a longitudinal study of sustainability in the UK hill sheep sector (A R Sibbald)

121 559 Strategic development of RS Technology for characterisation at the field scale (G G Wright)

121 560 Development and testing of risk management methodologies with respect to organic waste re-cycling on farms (W Towers)

121 561 The structuring of remote sensing and land cover knowledge for automated land cover change detection (A N R Law) [Non-commissioned]

121 598 Integrated system for analysing and reporting on the social, economic and environmental dimensions of rural land use change (R V Birnie) [Flexible Funding]

121 605 Validating the WEAVER complex systems modelling methodology (M P Hare)

121 606 Dynamic spatial modelling of one dimentionsal soil wate regimes for estimating risks to land use options. (G A Hudson)

121 607 The application of soil hydrological and land cover data to the regional modelling of gaseous nitrogen emissions (A Lilly)

121 608 Framework for evaluation and assessment of regional land use scenarios (FEARLUS) (A N R Law)

PROGRAMME UNIT 22

SOCIO-ECONOMIC AND POLICY ANALYSIS

Programme Unit Manager:
J R Crabtree

122 462 Spatial change in land use and agricultural structures - analysis and implications for rural sustainability (J R Crabtree) [Non-commissioned]

122 505 To develop and apply the concept of environmental accounting to farming systems, with specific reference to assessing their sustainability (J R Crabtree) [Flexible Funding]

122 562 Environmental benefits of traditional agricultural systems in European agriculture. A socio-economic analysis (D C Macmillan)

122 563 Choice experiments, cost effectiveness and related valuation methods for assessing the benefits from investment in the rural environment (C H Bullock)

122 564 Multi-objective programming models of farmer responses to environmental incentives and constraints (N J Barron)

122 565 Change in land use, agricultural and rural structures: implications for rural sustainability (J R Crabtree)

122 582 Socio-economics and agricultural impacts of the environmentally sensitive areas (ESA) scheme in Scotland (J R Crabtree) [Flexible Funding]

122 609 The development of alternative methodologies for the analysis of rural sustainability (Deborah Roberts)

PROGRAMME UNIT 23

ATMOSPHERIC DEPOSITION, LAND USE AND WATER QUALITY MANAGEMENT

Programme Unit Manager:
R C Ferrier

223 434 Influence of weathering of calcium-bearing minerals on the sensitivity of catchments to acidification (D C Bain)

223 457 Distributed modelling of water quality at the river basin scale (R C Ferrier) [Non-commissioned]

223 479 Nutrient cycling within semi-natural and managed ecosystem; consequences for water quality and catchment management (A C Edwards)

223 491 Critical loads of acidity to soils in relation to mineral weathering in different soil types (S J Langan)

223 492 Consequences of initial afforestation practices on catchment behaviour in northern Scotland (J D Miller)

223 500 The assessment of ground water quality in Grampian Region (A C Edwards) [Non-commissioned]

223 530 Water resource modelling: impacts of global change, atmospheric deposition, and land use change on soil and water quality (R C Ferrier)

223 531 Integration of soil hydrological information into existing physically-based catchment-scale models (A Lilly)

223 532 Nutrient changes in soil hydrochemistry between extensively managed hillslopes and output streams (H A Anderson)

223 533 Contribution and pathways of soil derived particles to the suspended loads of rivers (S J Hillier)

223 579 Significance of physical heterogeneity for scaling of solute

chemistry in soils from fine scale to subcatchment (A C Edwards) [Flexible Funding]

223 611 Characterisation of origins of disolved organic nitrogen (DON) and dissolved organic nitrogen (DOC) in upland soils (B L Williams)

PROGRAMME UNIT 24

SOIL QUALITY, CONTAMINATED LAND AND WASTE UTILISATION

Programme Unit Manager:
E Paterson

224 328 Effects on sewage sludge applications to agricultural soils and soil microbial activity and the implications for agricultural productivity and long term soil fertility (J R Bacon)

224 431 Effects of mineral-humic interactions in relation to modelling metal retention by soils (D Lumsdon)

224 432 Changes in time in the chemical association of the heavy metals cadmium, copper, lead, nickel and zinc in grassland and forest soils likely to receive sewage sludge (J R Bacon)

224 517 Assessment of the biological impact and remediation of oil contamination in soils (C D Campbell) [Non-commissioned]

224 535 Spatio-temporal modelling of opportunities and constraints associated with organic waste recycling on land (W Towers)

224 536 Sensitivity of Scottish agricultural and land use systems to atmospherically-derived radionuclide pollution (M V Cheshire)

224 537 The impact of dissolved and particulate organic matter derived from farm animal wastes on soil drainage water (H A Anderson)

224 538 Soil ecosystem recovery in relation to organic micropollutants and heavy metals (C D Campbell)

224 539 Modelling diffusive-convective transport of reactive solutes in soils (J C L Meeussen)

224 540 Plant availability of phosphorus from sewage sludge amended soil and the influence of heavy metals (C A Shand)

225 541 National assessment of factors and processes responsible for recent trends in the fertility of Scottish soils (A C Edwards)

225 544 Contribution of clay mineralogy to soil structural stability and release of mobile colloids from soils (E Paterson)

224 593 Modelling metal interactions with humic substances (E Paterson) [Non-commissioned]

224 602 Wastes to land-planning and design of a spatially based decision support tool (E Paterson) [Flexible Funding]

224 612 Microbial processes and diversity as quality indicators of soil subject to land use change (S J Chapman)

PROGRAMME UNIT 26

LAND USE OPTIONS FOR PLANTS

Programme Unit Manager: P Millard

326 435 Development of methods to measure seasonal nitrogen translocation in trees and their application to quantify internal cycling (P Millard)

326 436 Suitability of whole tree harvesting of Sitka spruce as a sustainable land use on different site types within the UK (M F Proe)

326 438 Phenotypic and genotypic basis of population dynamics in heterogeneous species - rich grassland (P Millard) [Flexible funding]

326 463 Interactions between N status and carbon partitioning on the development of *Vacciniuum* (P Millard) [Non-commissioned]

326 545 Consequences of defoliation for nutrient acquisition and root dynamics in a heterogenous soils environment (L A Dawson)

326 546 Models of carbon and nitrogen allocation, growth and remobilisation in plants of extensively managed pastures (C P D Birch)

326 547 Canopy size, nutrient supply and assimilate partitioning in native Scots pine seedlings (M F Proe)

326 591 Physiological and molecular responses of grasses to defoliation and their consequences for the vegetation dynamics of grazed swards. (B Thornton) [Director's Commissioned]

326 613 Acquisition and utilisation of nitrogen by plants of upland ecosystems (B Thornton)

PROGRAMME UNIT 27

NATURAL HERITAGE MANAGEMENT- VEGETATION DYNAMICS

Programme Unit Manager:
R J Pakeman

427 205 Effects of sheep grazing intensity on the vegetation dynamics of a range of wet heather moorlands differing in vegetation structure and species composition (A J Nolan)

427 450 Effects of pre- and post-burning management on the recovery of rehabilitated dry and wet heather moorland (P D Hulme)

427 487 Responses by tree saplings to browsing damage by cattle and red deer (A J Hester)

427 488 Influences on plant species balance in extensively managed grassland grazed by sheep and cattle (G T Barthram)

427 548 Extent and development of spatial aggregation of species in extensive grassland communities (C A Marriott)

427 549 Spatially explicit models of vegetation dynamics (C P D Birch)

427 585 Transitional Machair Systems of the Outer Hebrides (R J Pakeman) [Non-commissioned]

427 614 Maintenance and function of biodiversity in grazed systems: understanding the role of the regeneration niche (R J Pakeman)

PROGRAMME UNIT 28

NATURAL HERITAGE MANAGEMENT-HERBIVORE FORAGING

Programme Unit Manager: I J Gordon

428 448 Effect of social behaviour on foraging by ruminants in heterogeneous ecosystems (A M Sibbald)

428 449 Effect of shelter and food supply on behaviour and energy status of ruminants in heterogeneous upland ecosystems (A J Duncan)

428 485 Measurement of the ranging behaviour of red deer using a Global Positioning Satellite system to aid development of computer-based models (K D Farnsworth)

428 486 Functional basis for predicting interactions between red deer and natural vegetation communities (G R Iason)

428 489 Methods of estimating diet composition and intake by herbivores foraging in heterogeneous ecosystems (R W Mayes)

428 506 Quantity the role of species interactions during foraging on the functioning of mammalian communities (I J Gordon) [Non-commissioned]

428 522 Urinary metabolites as markers of dietary intake in free ranging ruminants (R W Mayes) [Non-commissioned]

428 550 Conditioned food aversions and their influence on the foraging behaviour of free-ranging ruminants (A J Duncan)

428 551 Determinants of habitat selection by wild rabbits and their influence on fragmentation of *Calluna* moorland (G R Iason)

428 552 Effects of spatial aggregation of grass species on frequency dependent in grazing herbivores (I J Gordon)

428 553 Spatial and temporal variation in population performance of red deer in relation to density, climate and land cover (I J Gordon)

428 573 The mechanistic basis of food selection by mountain hares and its importance on native woodland dynamics (G R Iason) [Non-commissioned]

428 588 Successional processes in upland vegetation: predicting critical herbivore loads over large spatial scales (A J Hester) [Flexible Funding]

428 615 Develop a theory for how large herbivore foraging decisions interact with the ecosystem processes at different spatio-termporal scales (K D Farnsworth)

PROGRAMME UNIT 29

LAND USE OPTIONS FOR ANIMALS

Programme Unit Manager: I A Wright

429 508 Pre and post-natal development of the reproductive axis in intrauterine growth restricted lambs (S M Rhind) [Non-commissioned]

429 554 Concentrations of environ-mental oestrogens (xenoestrogens) in tissues of domestic animals grazing pasture treated with sewage sludge (S M Rhind)

429 581 Neuroendocrine control of appetite and reproduction in sheep (S M Rhind) [Non-commissioned]

429 616 Estimating generic parameters for fibre quality traits in cahmere goats (Margaret Merchant)

429 617 Environmental effects on hair and wool follicle acivity in sheep and goats associated endocrine and paracrine control mechanisms (Stewart Rhind)

429 618 Developing and testing of models of animal foraging in mixed grazing of hereogeneous vegetation resources (Jonathan Beecham)

429 619 Matching animal genotype to nutritional resources in upland beef and sheep systems (Iain Wright)

429 620 Response of extensively reared animals to intensive handling (Pete Goddard)

429 621 Methods of assessment of motivation in ruminants (H W Erhard)

INTEGRATED PROGRAMME UNIT 36

SOIL-PLANT-ANIMAL INTERACTIONS

Integrated Programme Unit Manager: P Millard

536 398 Development and application of molecular biological techniques in studies of the interactions between microbes, nutrient cycling and vegetation among a range of agriculturally important pastures, to enable scaling from microcosm to field (S J Grayston) [Flexible Funding]

536 524 Influence of excretal urine-N on availability of soil phosphorus (C A Shand)

536 525 Soil nitrogen dynamics in urine patches in extensively managed sheep pastures (B L Williams)

536 526 Impact of grazing on microbial community structure and activity and the consequences for nutrient cycling (S J Grayston)

536 589 Colloid chemistry in Soil solution and its Impact on P Transfers from Grasslands (C A Shand) [Director's commissioned]

536 590 Plant stress effects on C:N efflux into the rhizosphere (S J Grayston) [Director's commissioned]

536 622 Rhizodeposition from grasses in relation to whole plant C-partitioning, ass affected by defoliation and nutrient supply in extensively managed grasslands, and associated impacts in soil microbial communities (E Paterson)

INTEGRATED PROGRAMME UNIT 37

LONG-TERM MEASUREMENT AND MONITORING OF CHANGE

Integrated Programme Unit Manager: J A Milne

537 493 Use of long-term monitoring sites and historical re-sampling strategies in the detection of environmental changes (J D Miller)

537 527 Development of methodologies for use in LCS 2000 (R V Birnie)

537 528 Development of methodology for large-scale habitat assessment (A J Nolan)

537 529 Design of strategies for environmental and compliance monitoring (J R Crabtree)

537 587 Effect of change in grazing pressure of sheep on erosion and vegetation cover on Trotternish Ridge (J A Milne) [Flexible Funding]

537601 Modelling plant and animal biodiversity associated with a Scottish catchment devoted to agriculture (J A Milne) [Flexible Funding]

537 623 Environmental Change Network: measure long-term changes in climate, soils, vegetation and wildlife populations at two upland sites in Scotland (D J Henderson)

537 624 Integrating remotely sensed vegetation indices with biophysical data to provide measures of the structure and biomass of upland vegetation types (G G Wright)

INTEGRATED PROGRAMME UNIT 38

DEVELOPMENT OF DECISION SUPPORT SYSTEMS

Integrated Programme Unit Manager: J A Milne

538 494 MLURI Data Model (A N R Law)

538 534 Construction of a land use modelling environment to aid decision support tool development (J A Milne)

538 584 Aiding the application of HILLDEER by Deer Commission for Scotland and deer managers in Scotland (J A Milne) [Flexible Funding]

538 625 Development of a decision support tool for the management of upland vegetation, with a wide range of applications (J A Milne)

MLURI EXTERNAL CONTRACTS

LAND USE SCIENCE GROUP

121 569 Hydrology of Alpine High Latitude Basins (HYDALP) (G G Wright) [European Commission]

121 577 Developing agroforestry systems for the Southern Hill Region of the Yangtze River (A R Sibbald) [The Royal Society]

121 599 Modelling environmental impacts of land use change (A R Sibbald) [DETR]

ENVIRONMENTAL AND SOCIO-ECONOMICS GROUP

122 574 Improving Agri-environmental policies: A simulation approach to the role of the cognitive properties of farmers and institutions (J R Crabtree) [European Commission]

SOIL SCIENCE GROUP

223 474 Prediction of spatial and temporal variation in the solute chemistry of a major river system from the integration of models of terrestrial and hydrological processes (S J Langan) [NERC]

223 478 Dynamic models to predict and scale-up the impact of environmental change on biogeochemical cycling (R C Ferrier) [European Commission]

223 507 Total nitrogen and phosphorus losses from upland ecosystems: significance of instream processes (P J Chapman) [NERC]

223 523 Ecological effects of land use changes on European terrestrial mountain ecosystems (ECOMONT) (R C Ferrier) [Centre for Ecology and Hydrology]

224 520 Trace metal and phosphate extraction from sediments and soils (J R Bacon) [European Commission]

224 568 The reduction of 137Cs and 90 Sr uptake by grass in natural meadows (C A Shand) [European Commission]

224 571 Effects of afforestation of agricultural land on heavy metal mobility in soil (D C Bain) [European Commission]

225 572 Comparative evaluation of European methods for sampling and sample preparation of soils (J R Bacon) [European Commission]

224 626 Integrated assessment and modelling of soil containment behaviour, transport and impact at remediable urban sites (E Paterson) [NERC]

224 467 Multicomponent transport of reactive chemicals in physically and chemically heterogeneous systems (J C L Meeussen) [Macaulay Development Trust]

ECOLOGY AND ANIMAL SCIENCE GROUP

428 503 The influence of trituration surface and molar wear on assimilation efficiency and its relationship with fitness of Soay sheep (I J Gordon) [European Commission]

428 504 The herbivore's dilemma: Trade-offs between nutrition and parasitism in foraging decisions (I J Gordon) [NERC]

428 521 Long-term consequences of contaminated semi-natural environments - an integrated approach (R W Mayes) [European Commission]

428 578 Effects of food-borne glucosinolates on human health (A J Duncan) [European Commission]

428 592 Natural resources management within multispecies systems in the mid-Zambezi Valley: Implications for sustainable development in dry lands area of Southern Africa (I J Gordon) [European Commission]

428 594 Environmental variability and productivity of semi arid grazing systems (I J Gordon) [Natural Resources Institute]

428 603 The implication of changing management policy for the performance of red deer populations across Scotland (I J Gordon) [Deer Commission for Scotland]

429 476 The role of domestic livestock systems in rural development in disadvantaged areas (J A Milne) [European Commission]

429 499 Selection of goats for resistance to gastro-intestinal nematodes (I A Wright) [SOAEFD]

429 511 Increasing competitiveness of high quality European animal textile fibres by improving fibre quality (J A Milne) [European Commission]

429 566 European Livestock Policy Evaluation Network: development of protocols and methodologies for policy evaluation and impact on rural development (I A Wright) [European Commission]

INTEGRATED PROGRAMME UNITS

537 580 Rapid habitat condition assessment of six deer management group areas and determination of the repeatability and accuracy of a range of methods for carrying out such assessments (J A Milne) [Deer Commission for Scotland/SNH]

MRCS CONSULTANCY DIVISION

539 415 Monitoring of Environmentally Sensitive Areas in Scotland (J H Gauld) [SOAEFD]

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CONFERENCES and VISITS ABROAD

UK Conferences attended by staff during 1997

LAND USE SCIENCE GROUP

AGNEW, R D M. UK Agroforestry Research Forum, Annual Meeting. Cranfield University, 7–9 July.

ASPINALL, R J. TERRA 3. University College, Chester, 7-8 April.

BENNETT, A J. Diffuse Pollution & Agriculture. Edinburgh University, 9-10 April.

BENNETT, A J. Fertiliser Management & Use. Cambridge, 11-12 December.

BIRNIE, R V. CS2000 Workshop on Land Cover Mapping. University of York, 24-25 March.

BIRNIE, R V. Estate Management in Upper Deeside. Blairgowrie, 13-15 May.

BROADGATE, M L. Snow Conference. Stirling, 19 March.

BROADGATE, ML. STORMS, Braemar. 29 April-4 May.

BROOKER, N A. Mapping Off The Web. University of Glasgow, 21 February.

DALZIEL, A J I. Agroforestry. Cranfield University, 7-9 July.

HARE, M P. British Ecological Society, Winter Meeting. Warwick University, 16-18 December.

HUDSON, G. Statistics in Meteorology. The Meteorological Office, Bracknell, 16 January.

HUDSON, G. Environmental Statistics. University of Glasgow, 11 March.

HUDSON, G. Spatial Statistics. Open University, 17 December.

HUMBLE, A. IALE UK 97:Species Dispersal and Land Use Processes. University of Ulster, N.I., 9-11 September.

JONES, K H. GIS Research 5th National Conference. University of Leeds, 8-11 April.

MACLEAY, S. National Geospatial Data Framework Intergraph (UK). Swindon, 9 December.

MATTHEWS, K B. Information transfer in agriculture. SCI, London, 21 October.

MILLER, D R. Environmental Management & Planning. Dunblane Hydro, 20-21 February.

MILLER, D R. STORMS. Braemar, 29 April-4 May.

MILLER, D R. Forest Fare. Glen Tanar, 5 June.

MILLER, D R. Wind Energy. University of Heriot Watt, 17 July.

MILLER, D R. ERDAS UK Users Group. Cambridge, 15-16 September.

MITCHELL, J A. Estate Management in Upper Deeside. Blairgowrie, 13-15 May.

SIBBALD, A R. UK Agroforestry Research Forum Committee. Birmingham, 14 February.

SIBBALD, A R. UK Agroforestry Research Forum Annual Meeting. Cranfield University, 7-9 July.

TOWERS, W. Scottish Planning and Environmental Law Conference. Dunblane, 20 February

TOWERS, W. Predicting the Yield of Short Rotation Coppice. ETSU, Hanwell, Oxon, 27 February.

TOWERS, W. Soil Protection. Scottish Soils Discussion Group. Ayr, 19 March.

WHERRETT, J R. IALE UK 97: Species Dispersal and Land Use Processes. University of Ulster, NI., 9-11 September.

WRIGHT, G G. Observations and Interactions – 23rd Annual Conference of Remote Sensing Society. University of Reading, 2-4 September.

WRIGHT, G G. ERDAS UK Users Group Meeting. Cambridge, 15-16 September.

WRIGHT, G G. 'The Way Forward' – Environmental Health Promotion. Stirling, 20-21 November.

ENVIRONMENTAL AND SOCIO-ECONOMICS GROUP

BARRON, N-J. Agricultural Economics Society Annual Conference. Edinburgh, 21-24 March.

BARRON, N-J. EU Images Meeting. Edinburgh, 8-11 June.

BARRON, N-J. Grassland Management in ESA. University of Lancaster, 23-25 September.

BARRON, N-J. Agri-Environmental Policy Mechanisms. Royal Society, London, 2 December.

CRABTREE, J R. Agricultural Economics Society. Edinburgh, 21-23 March.

CRABTREE, J R. BGS Symposium on ESA's. University of Lancaster, 23-25 September.

CRABTREE, J R. Environmental Economic Instruments. London, 1-2 December.

CRABTREE, J R. Environmental Protection 1997: Managing the Local Environment, 22-23 October.

CRABTREE, J R. Agricultural Economic Society. London, 2 December.

HILL, G W. Sustainable Development in Scotland. University of Edinburgh, 19 March.

HILL, G W. International Sustainable Development Research. Manchester Conference Centre, 7-8 April.

MACMILLAN, D C. Nature and People on a Highland Estate: 1500-2000. Edinburgh, 9-10 May.

THORBURN, A P. IALE UK 97:Species dispersal and land use processes. University of Ulster, N.I., 9-11 September.

THORBURN, A P. Native Woodlands Policy Forum: the role of strategies for native woodlands. Pitlochry, 4 December.

VAN DER HORST, D. Sustainable Development in Scotland. University of Edinburgh, 19 March.

VAN DER HORST, D. International Sustainable Development Research. Manchester Conference Centre, 7-8 April.

VAN DER HORST, D. Developing an environmental agenda in Scotland. Elgin, 7 May.

SOIL SCIENCE GROUP

BACON, J R. Scottish Soils Discussion Group. Auchencruive, 19-20 March.

BACON, J R. Atomic Spectroscopy Updates. Edinburgh, 24-25 March.

BACON, J R. Environmental Geo-chemistry and Health. Edinburgh, 12 June.

BAIN, D C. Clay Mineralogy-Past, Present and Future, Aberdeen, 9-11 April.

BAIN, D C. Clay Mineral Evolution. Nottingham, 13-14 November.

CAMPBELL, C D. Sustaining our Soils. British Society for Soil Science, London, 6 March.

CAMPBELL, C D. Scottish Soils Discussion Group, Auchincruive, 19-20 March.

CAMPBELL, C D. DETR Sustainability Indicators Working Group. London, 28 May.

CAMPBELL, C D. DETR Workshop on Critical Loads for Heavy Metals. London, 15 October.

COULL, M C. Scottish Soils Discussion Group. Auchincruive, 19-20 March.

DUNN, S M. National Hydrology Symposium. University of Salford, 15-18 September.

FERRIER, R C. Sustaining our Soils. British Society for Soil Science, London, 6 March.

FERRIER, R C. GCTE-TERI Workshop. Silwood Park, London, 24-27 June.

FRASER, A R. Clay Mineralogy – Past, Present & future. Aberdeen, 10-11 April.

FRASER, A R. Modern Trends in FTIR & FTIR Sampling. Aberdeen, 16 September.

HELLIWELL, R C. Snow Resources in Scotland. Bridge of Allan, Stirling, 19 March.

HELLIWELL, R C. Surface Water Acidification. University College, London, 11-12 September.

HILLIER, S J. Clay Mineralogy, Past, Present & Future. Aberdeen, 10-11 April.

HILLIER, S J. Measurement & Application of Stable Isotopes. Aberdeen, 2 July.

HILLIER, S J. BGS. Nottingham, 13-14 November.

LANGAN, S J. Soil Sustainability. London, 6 March.

LANGAN, S J. Increasing Role of N Deposition. London, 8 September.

LANGAN, S J. Critical Loads – Nitrogen. London, 11 September.

LANGAN, S J. National Society for Clean Air & Environmental Protection. Glasgow, 20-23 October.

McMURRAY, E M. 25th Scottish Microscopy Group Symposium. Dunblane, 12 September.

MILLER J D. IEA. Dumfries, 22 September.

PATERSON, E. Clay Mineralogy Past, Present & Future. Aberdeen, 10-11 April.

WADE, A J. Land Ocean Interaction Study Review. Hull University, 18-20 March.

PLANT SCIENCE GROUP

CHAPMAN, P J. Freshwater Acidification: The Increasing Importance of Nitrogen. University College, London, 11 September.

DAWSON, L A. Workshop of Malaysian National Research Project into Restoration of Disturbed Mountain Sites. ITE, Banchory, Aberdeenshire, 2-3 October.

DAWSON, L A. Workshop on Molecular and Physiological Approaches to Studying Plant Vegetation Dynamics. SCRI, Dundee, 10 December.

EDWARDS, A C. Land Ocean Interaction Study Review. Hull University, 18-20 March.

EDWARDS, A C. Diffuse Pollution Meeting, Edinburgh, 9-11 April.

EDWARDS, A C. Managing Risks of Nitrates to Humans & the Environment. Colchester, 1-2 August.

EDWARDS, A C. Fertiliser Management and Use. Cambridge, December.

GRAYSTON, S J. BBSRC/SOAEFD Plant-Soil-Microbe Interactions Initiative Meeting. University of Oxford, 16-19 March.

GRAYSTON, S J. Grassland Management in the ESA's. University of Lancaster, 23-25 September.

GRIFFITHS, J. International Energy Agency Conference: Indicators of Sustainable Forest Management, Eddleston, Nr Peebles, 20-25 September.

MARRIOTT, C A. 5th BGS Research Conference. University of Plymouth, 8-10 September.

MILLARD, P. Major Biological Issues Resulting from Anthropogenic Disturbance of the Nitrogen Cycle. Lancaster University, 3-5 September.

PATERSON, E. British Society of Soil Science Jubilee meeting. Newcastle, 9-11 September.

PROE, M F. International Energy Agency Conference: Indicators of Sustainable Forest Management, Eddleston, Nr Peebles, 20-25 September.

SHAND, C D. Measurement & Application of Stable Isotopes. Aberdeen, 2 July.

THORNTON, B. SEB Annual Meeting. University of Kent, 7-11 April.

THORNTON, B. 5th BGS Research Conference. University of Plymouth, 8-10 September.

THORNTON, B. SOAEFD, Vegetation Dynamics Workshop 1997. SCRI, 10 December.

WILLIAMS, B L. Freshwater Acidification: The Increasing Importance of Nitrogen. University College London, 11 September.

ECOLOGY AND ANIMAL SCIENCE GROUP

BARTHRAM, G T. 5th British Grassland Society Research Conference. University of Plymouth, 8-10 September.

BEECHAM, J A. British Ecological Society Winter Meeting. Warwick, 16-18 December.

BIRCH, C P D. Clonal Plants & Environmental Heterogeneity. University of Wales, Bangor, 9-14 September.

BIRCH, C P D. Agricultural Research Modellers Meeting. London, April.

BUGALHO, M. British Ecological Society Winter Meeting. Warwick, 16-19 December.

DENNIS, P. Biodiversity & Ecosystem Processes: Theory & Modelling. Silwood Park, London, 24-27 June.

DENNIS, P. Species Dispersal and Land Use Processes. University of Ulster, NI., 9-11 September.

DENNIS, P. Biodiversity and Systematics Conference. Royal Museum of Scotland, Edinburgh, 13 October.

GODDARD, P J. International Society Applied Ethology Winter Meeting: Motivation and Animal Welfare. Royal Veterinary College, London, 3 December.

GODDARD, P J. British Society of Animal Science Winter Meeting. Scarborough, 24-26 March.

GODDARD, P J. Veterinary Deer Society. University of Edinburgh, 15-16 May.

ERHARD, H W. International Society of Applied Ethology Winter Meeting: Motivation and Animal Welfare. Royal Veterinary College, London, 3 December.

GORDON, I J. Population Ecology and Management of Deer. The Manchester Metropolitan University, 9-10 April.

GORDON, I J. British Ecological Society Winter & Annual General Meeting. University of Warwick. 16-18 December.

HENDERSON, D J. Grassland Management in Environmental Sensitive Areas. University of Lancaster, 23-25 September.

HESTER, A J. Native Woodland Discussion Group Annual Field Meeting. Ardtornish, Morven, 5-8 June.

HESTER, A J. British Ecological Society Winter Meeting. University of Warwick, 16-18 December.

HULME, P D. Blanket Mire Degradation. University of Manchester, 8-11 April.

HULME, P D. Mires Research Group Field Meeting. Connemara, Galway, 14-20 September.

MILNE, J A. British Society of Animal Science Winter Meeting. Scarborough, 24-26 March.

MILNE, J A. Grassland Management in the ESA's. Lancaster Univeristy. 23-25 September.

NOLAN, A J. Grassland Management in ESA's. Lancaster University. 23-25 September.

PAKEMAN, R J. British Ecological Society Winter Meeting. University of Warwick, 16-18 December.

PARTRIDGE, L W. Population Ecology & Management of Deer. The Manchester Metropolitan University, 9-10 April.

RAO, S. British Ecological Society Winter Meeting. University of Warwick, 16-18 December.

RHIND, S M. British Society of Animal Science Winter Meeting. Scarborough, 24-26 March.

RHIND, S M. British Endocrine Society Annual Meeting. Harrowgate, 7-10 April.

SIBBALD, A M. International Society of Applied Ethology Winter Meeting: Motivation and Animal Welfare. Royal Veterinary College, London, 3 December.

VILLAR, D. British Society of Animal Science Winter Meeting. Scarborough, 24-26 March.

WERKMAN, B R. Species Dispersal & Land Use Processes. Coleraine, N.I., 9-11 September.

WILLIAMS, S M. 'ELPEN' Steering Committee Meeting. London, 26 May.

WILLIAMS, S M. 'ELPEN' Project Meeting. Ministry of Agriculture, Fisheries and Food, London, 18 September.

WRIGHT, I A. British Society of Animal Science Winter Meeting. Scarborough, 24-26 March.

WRIGHT, I A. The Potential Role of Rare Livestock Breeds in UK Farming Systems. Appleby, Cumbria, 1-2 December.

ANALYTICAL GROUP

HEPBURN, A. The Measurement and Application of Stable Isotopes. MLURI, Aberdeen, 2 July.

OWEN, I J. Soil Protection (Scottish Soils Discussion Group). Auchincruive, Ayr, 19 March.

NEWMAN, G E. SCLAF – Interlab Testing Sub-group. University of Glasgow, 25 March.

SINCLAIR, L J. The Measurement & Application of Stable Isotopes. MLURI, Aberdeen, 2 July.

SMITH, A. ECN Analytical Meeting. Forestry Commission, Alice Holt, 11 March.

SMITH, A. Sixth International Symposium on Chemistry in the Oil Industry. Ambleside, Cumbria, 14-17 April.

SMITH, A. The Measurement & Application of Stable Isotopes. MLURI, Aberdeen, 2 July.

STEWART, A M. The Measure & Application of Stable Isotopes. MLURI, Aberdeen, 2 July.

STUART, A W. BBSRC Engineers Conference 1997. John Innes Centre, Norwich, 10-11 September.

COMPUTING & INFORMATION SERVICES GROUP

McGUINNES, J A. Serials Administration & Management. Edinburgh Office. Conference Venue, 19 February.

ROBERTSON, L E. Internet and Land Based Industries. University of Glasgow, 2 September.

ADMINISTRATION GROUP

BIRD, S P. Marketing for Technologists. Monklands Enterprise, Lanarkshire, 29 August.

LUND, J. Managing the Media. Edinburgh, 12 June.

SLATER, D J. Corporate Governance in the next Millennium, Robert Gordon University, Aberdeen, 29 August.

MACAULAY RESEARCH & CONSULTANCY SERVICES

GAULD, J H. Sustaining our Soils. London, 6 March.

GAULD, J H. British Society of Soil Science, Annual Meeting. University of Newcastle, 7-11 September.

GAULD, J H. ESA, Grassland Management. University of Lancaster, 23-25 µ

GAULD, J H. Soil Protection & Industry. Silsoe, 24 September.

MALCOLM, A. Native Woodland Restoration in S. Scotland, Principles and Practice. Royal Botanic Gardens, Edinburgh, 21 November.

Conferences abroad attended by staff during 1997

LAND USE SCIENCE GROUP

ASPINALL, R J. GIS and Environmental Modelling. ANU, Canberra, Australia, 20-24 January.

ASPINALL, R J. GIS and Ecology, Centre for GeoInformatics. Stockholm, Sweden, 17 February.

BIRNIE, R V. Geo-Information for Sustainable Land Management. ITC Enschede, 17-21 August.

BIRNIE, R V. Monitoring of Land Use Changes. SC-DLO, Wageningen, 17-19 September.

GIMONA, A. Joint European Conference on Geographic Information. Vienna, April.

HUDSON, G. Precision Agriculture: Spatial and Temporal Variability in Environmental Quality. Wageningen, The Netherlands, 20-24 January.

LILLY, A. Characterisation and Measurement of Hydraulic Properties. US Salinity Lab, California, USA, 22-24 October.

MILLER, D R. Joint European Conference on GIS. Vienna, Austria, 15-18 April.

SIBBALD, A R. Agroforestry and Land Use Management International Workshop. Montpelier, France, 23-29 June.

SIBBALD, A R. Annual Meeting of EAAP. Vienna, Austria, 25-29 August.

WHERRETT, J R. Data Visualisation: Previewing the Future. Missouri, USA, 8-10 October.

WHERRETT, J R. Urban Regional Environmental Planning and Informatics to Planning in an Era of Transition. Athens, Greece, 22-24 October.

ENVIRONMENTAL AND SOCIO-ECONOMICS GROUP

BULLOCK, C H. EAERE Conference. Netherlands, June.

CRABTREE, J R. Rural Restructuring. Dijon, France, 20-21 March.

CRABTREE, J R. Sustainability Workshop. The Hague, Netherlands, 17-20 April.

CRABTREE, J R. European Environmental Economics Conference. Tilburg University, Netherlands, 26-28 June.

MACMILLAN, D C. EAERE Conference. Netherlands, June.

MACMILLAN, D C. World Forestry Congress. Antalya, Turkey, 13-22 October.

SOIL SCIENCE GROUP

BACON, J R. 11TH Conference on Heavy Metals in the Environment. Washington, September.

BAIN, D C. International Clay Conference. Ottawa, Canada, 15-21 June.

BAIN, D C. Weathering in Acid Conditions/ Weathering of Industrial Wastes. Bratislava, Slovakia, 24-26 November.

CAMPBELL, C D. SSSA Annual Meeting. Anaheim, USA, 27-31 October.

CHAPMAN, XIII Interntional Symposium on Environmental Biogeochemistry, Monopoli (Bari), Italy, 21-26 September.

FERRIER, R C. 7th Stockholm Water Symposium. Sweden, 11-14 August.

FERRIER, R C. 4th Ecosystems Manipulation Workshop. Jasper, Canada, 14-17 October.

HILLIER, S J. Quantitative Clay Mineral Analysis Conference. Trier, Germany, 18-21 September.

HODSON, M. Seventh Annual V.M. Goldschmidt Conference. Tucson, Arizona, USA, 1-6 June.

HODSON, M. Mineral Weathering. Penn. State University, USA, 14-25 June.

LUMSDON, D G. 4th International symposium on Environmental Geochemistry. Vail, Colorado, USA, 5-10 October.

MEEUSSEN, J C L. 213th Meeting American Chemical Society. San Francisco, USA, 13-17 April.

PLANT SCIENCE GROUP

DOMBURG, P. Pedometrics '97. Wisconsin, USA, 18-20 August.

DOMBURG, P. Fertilisation for Sustainable Plant Production and Soil Fertility. Gent, Belgium, 7-13 September.

GRAYSTON, S J. Conference – INRA Twinning. Dijon, France.

GRAYSTON, S J. EU Eurosilva Workshop. Finland.

GRAYSTON, S J. EU Cost Action Workshop-Tree Physiology Research. Saariselka, Lapland, 4-7 September.

MARRIOTT, C A. International Grassland Congress. Winnipeg, Canada, 8-19 June.

WILLIAMS, B L. Agricultural Uses of Peatlands. St Malo, France, 25-29 August.

ECOLOGY AND ANIMAL SCIENCE GROUP

BEECHAM, J A. Ecological Modelling. Pula, Croatia, 16-19 September.

BIRCH, C P D. 18th International Grassland Congress. Winnipeg & Saskatoon, Canada, 8-19 June.

BIRCH, C P D. Modelling Growth & Allocation in Grass Workshop. Lusignan, France, 16-17 December.

BUGALHO, M. Portuguese Ecological Society Annual Meeting. Coimbra, Portugal, 3-5 December.

DENNIS, P. Research and Biodiversity Workshop, SEPA. Stockholm, Sweden 9-13 April.

DUNCAN, A J. International Symposium on Poisonous Plants. Texas, USA, 18-23 May.

FARNSWORTH, K D. Sustainability in Boreal Regions. Itasca, USA, 5-10 October.

FORSTER, J. Annual Meeting of the Spanish Grassland Society. Seville, Spain, 5-7 May.

GODDARD, P J. Congress of International Society for Applied Ethology. Prague, August.

GORDON, I J. Herbivores, Plants & Predators. Wageningen, The Netherlands, 14-16 April.

GORDON, I J. International Grassland Congress. Canada, June.

HESTER, A J. Herbivores, Plants & Predators. Wageningen, The Netherlands, 14-16 April.

IASON, G R. Herbivores, Plants & Predators. Wageningen, The Netherlands, 14-16 April.

LAKER, J. First International Conference of the Livestock Systems in Integrated Rural Development Network. Napflio, Greece, 23-25 January.

MILNE, J A. First International Conference of the Livestock Systems in Integrated Rural Development Network. Napflio, Greece, 23-25 January.

MILNE, J A. European conference on Meat and Bone Meal. Brussels, Belgium, 23-25 September.

WERKMAN, B. Herbivores, Plants & Predators. Wageningen, The Netherlands, 14-16 April.

WRIGHT, I A. First International Conference of the Livestock Systems in Integrated Rural Development Network. Napflio, Greece, 23-25 January.

Staff visits abroad during 1997

LAND USE SCIENCE GROUP

BIRNIE, R V. Joint Project. Institute of Soil Science, Nanjing, China, 1-17 October.

BROADGATE, M L. EC Project Meeting (HYDALP), Berne, Switzerland. 15-19 November.

HARE, M P. SWARM User Meeting. Santa Fe Institute, New Mexico, 14-17 February.

HUDSON, G. (HYPRES) Database. INRA, Orleans, France, 11-20 June.

HUDSON, G. Soil Sampling. Basle, Switzerland, 29 August-1 September.

HUDSON, G. HYPRES Database and its Uses. University of Naples, Italy, 2-5 October.

JONES, K H. GENSYM Course. Cambridge, Mass, U.S.A., 8-25 January.

LILLY, A. EU HYPRES Database. INRA, Orleans, France, 11-20 June.

LILLY, A. HYPRES Database and its Uses. University of Naples, Italy, 2-5 October.

MILLER, D R. EC Project Meeting (HYDALP). Innsbruck, 3-5 March.

MILLER, D R. EC Project Meeting (HYDALP). Berne, Switzerland, 15-19 November.

MORGAN-DAVIES, J. EC Project Meeting (HYDALP). Innsbruck, 3-5 March.

SIBBALD, A R. Project Meeting – INRA Twinning. Clermont Ferand, March.

WRIGHT, G G. EC Project Meeting (HYDALP). Innsbruck, 3-5 March.

ENVIRONMENTAL & SOCIO-ECONOMICS GROUP

CRABTREE J R. EC Project Meeting. Paris, 17 January.

CRABTREE J R. EC Project Meeting. Umea and Helsinki, 21-24 January.

CRABTREE, J R. EC Project Meeting. Paris, 28 April.

CRABTREE, J R. EC Project Meeting. Vienna, Austria, 29-31 October.

SOIL SCIENCE GROUP

BACON, J R. Soil Sampling. Basle, Switzerland, 29 August – 1 September.

BACON, J R. EC Project Meeting. Bordeaux, France, 4-5 December.

BAIN, D C. Podzolisation Project Meeting. Finland, 8-11 February.

BAIN, D C. EU Project Meeting. Denmark, Sweden, 16-19 April.

CAMPBELL, C D. American Society of Microbiology. Pennsylvania,

CAMPBELL, C D. USDA Soil Microbial Systems. University of Delaware, Beltsville, Maryland, USA.

CHAPMAN, S J. GCTE Focus 4 Workshop. Frankfurt, Germany, 20-22 October.

CHESHIRE, M V. EC Project Meeting. Barcelona, Spain, 15-18 February.

FERRIER, R C. Magic Group Workshop. Florida, U.S.A., 5-14 January.

FERRIER, R C. Magic-Wand Workshop. Virginia, U.S.A., 17-25 June.

LANGAN, S J. Collaborative Research Meeting. New Brunswick, Canada, 25 - 30 September.

LANGAN, S J. Collaborative Meeting. Nanjing, China.

MEEUSSEN, H C L. EC Meeting. Paris, 25 March.

WILSON, M J. EC Project Meeting. Kiev, Ukraine, 1-8 March.

PLANT SCIENCE GROUP

DAWSON, L A. Royal Society Collaborative Research Project. Lusignan, France, 25 June-28 July.

EDWARDS, A C. University of Remmes, France, December.

EDWARDS, A C. EC Cost Action. Brussels.

GRAYSTON, S J. Collaboration. Finnish Forest Research Institute, Vantaa, Finland, 8-10 September.

GRAYSTON, S J. Collaboration. University of Helsinki, Finland, 8-10 September.

MILLARD, P. INRA/MLURI Twinning. Clermont Ferrand, Lusignan & Paris, France, 26-30 May.

MILLARD, P. Collaboration. Agriculture and Agri-Food, University of Victoria, British Columbia, Canada, 21-30 August.

PROE, M F. EU Concerted Action Meeting, Lisbon, Portugal, May.

THORNTON, B. British Council Alliance Project, INRA-CAEN, France. 22 September-3 October.

WENDLER, R. Collaboration. Landcare Research Institute, Lincoln and Canterbury University, Christchurch, New Zealand, 17 February-17 March.

ECOLOGY & ANIMAL SCIENCE GROUP

BEECHAM, J A. INRA/MLURI Twinning Workshop on Grazing Ecology. Theix, France, 17-19 November.

BIRCH, C P D. Collaboration. Hokkaido, Japan, July

DENNIS, P. Norwegian Institute for Nature Research. Oslo, Sweden, 23-27 April.

DUNCAN, A J. Collaboration. Utah, May.

DUNCAN, A J. Workshop on Utilisation of High Mountain Pastures in Northern Pakistan. Gilgit, Pakistan, 28 July-8 August.

FARNSWORTH, K D. Collaboration. Instituto per la Fauna Silvatica, Italy, September.

FARNSWORTH, K D. Collaboration. University of Minnesota, USA, October.

FARNSWORTH, K D. INRA/MLURI Twinning Workshop on Grazing Ecology. Theix, France, 17-19 November.

FARNSWORTH, K D. Modelling Herbivore Foraging Workshop, Clermont Ferrand, France, 18-19 November.

GODDARD, P J. British Council Collaborative Project. University of Onlu, Finland, 2-5 October.

GORDON, I J. Workshop on Utilisation of High Mountain Pastures in Northern Pakistan. Gilgit, Pakistan, 28 July-8 August.

GORDON, I J. INRA/MLURI Twinning Workshop on Grazing Ecology. Theix, France, 17-19 November.

GORDON, I J. Modelling Herbivore Foraging Workshop, Clermont Ferrand, France, 18-19 November.

HESTER, A J Workshop on Utilisation of High Mountain Pastures in Northern Pakistan. Gilgit, Pakistan, 28 July-8 August.

IASON, G R. Collaboration Meeting, EU Landscape Programme, Stockholm, Sweden, 1-5 February.

IASON, G R. Collaborative Fieldwork. Umea, Sweden, 5-14 March.

IASON, G R. Collaboration Meeting, EU Landscape Project. Grimso, Sweden, 25-30 October.

MAYES, R W G R. Collaboration Meeting, EU Landscape Programme, Stockholm, Sweden, 1-5 February.

MAYES, R W. Collaborative Fieldwork. Umea, Sweden, 5-14 March.

MAYES, R W. Collaboration Meeting, EU Landscape Project. Grimso, Sweden, 25-30 October.

MILNE, J A. INRA/MLURI Twinning Workshop on Grazing Ecology. Theix, France, 17-19 November.

MILNE, J A. Modelling Herbivore Foraging Workshop, Clermont Ferrand, France, 18-19 November.

REDDEN, H L. Optical Fibre Diameter Analysis Training Course. Aachen, Germany, 3-6 September.

WILLIAMS, S M. Livestock Systems in Integrated Rural Development (LSIRD) Workshop. Granada, Spain, 23-24 May.

WILLIAMS, S M. 'ELPEN' Project Meeting. European Commission, Brussels, 23-24 June.

WILLIAMS, S M. 'ELPEN' Project Meeting. Federal Ministry of Agriculture, Food and Forestry, Bonn, Germany, 15-16 October.

WILLIAMS, S M. 'ELPEN' Project Meeting. Saxon Agricultural Institute, Leipzig, Germany, 15-16 October.

WILLIAMS, S M. 'ELPEN' Project Meeting. Institut de L'Elevage, Paris, France. 21-22 October.

WILLIAMS, S M. 'ELPEN' Project Meeting. Ministry of Agriculture, Paris, France, 21-22 October.

WILLIAMS, S M. 'ELPEN' Project Meeting. Ministry of Agriculture and Forestry, Vienna, Austria, 29-30 October.

WILLIAMS, S M. 'ELPEN' Project Meeting. Ministry of Agriculture and Board of Agriculture, Stockholm, Sweden, 14 November.

WILLIAMS, S M. 'ELPEN' Protocol Working Group. Wageningen, The Netherlands, 10-11 December.

WRIGHT, I A. British Council Collaborative Project. Centro de Investigacion, Apliande & Technologia, Spain, 10-14 April.

WRIGHT, I A. Workshop on Utilisation of High Mountain Pastures in Northern Pakistan. Gilgit, Pakistan. 28 July- 8 August

WRIGHT, I A. Modelling Herbivore Foraging Workshop, Clermont Ferrand, France, 18-19 November.

ANALYTICAL GROUP

MIDWOOD, A J Collaborative Research. Texas A&M University, Texas, USA, 12-21 May.

SMITH, A. Rural Development Administration. Suwon, Seoul, South Korea, 27 October-5 November.

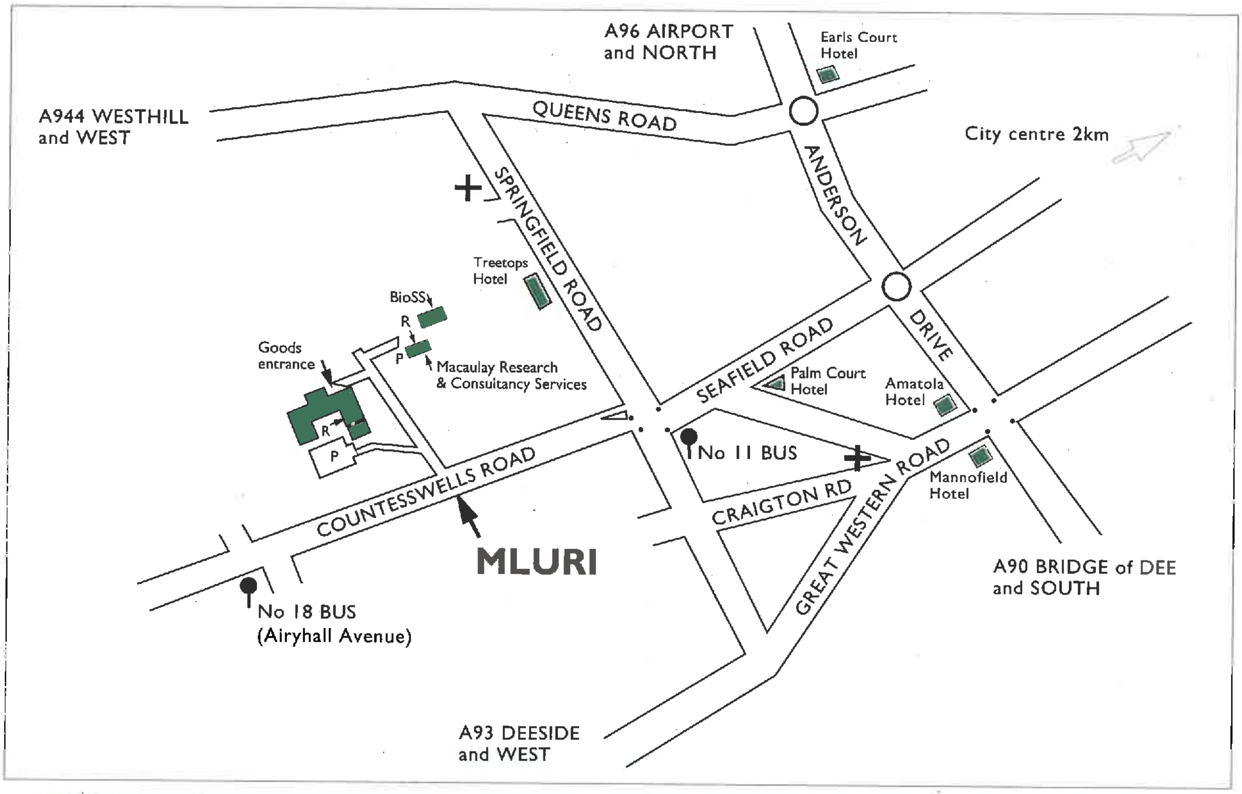
ANNUAL FINANCE STATEMENT for the YEAR ENDING 31 MARCH 1997

Income	£k
Scottish Office Agriculture, Environment and Fisheries Department	5,897
SOAEFD Flexible Research Funding and other SOAEFD contracts	978
European Union research contracts	373
Funding from other Government Departments, Public Bodies and Agencies	85
Private research and consultancy contracts	222
Other income	134
	7,689
less Income deferred or applied to capital purchases	-117
Total income	**7,572**
Expenditure	
Staff costs	5,158
Research expenditure including Research Station costs	1,139
Other operating costs	1,327
	7,624
Surplus (deficit)	(52)

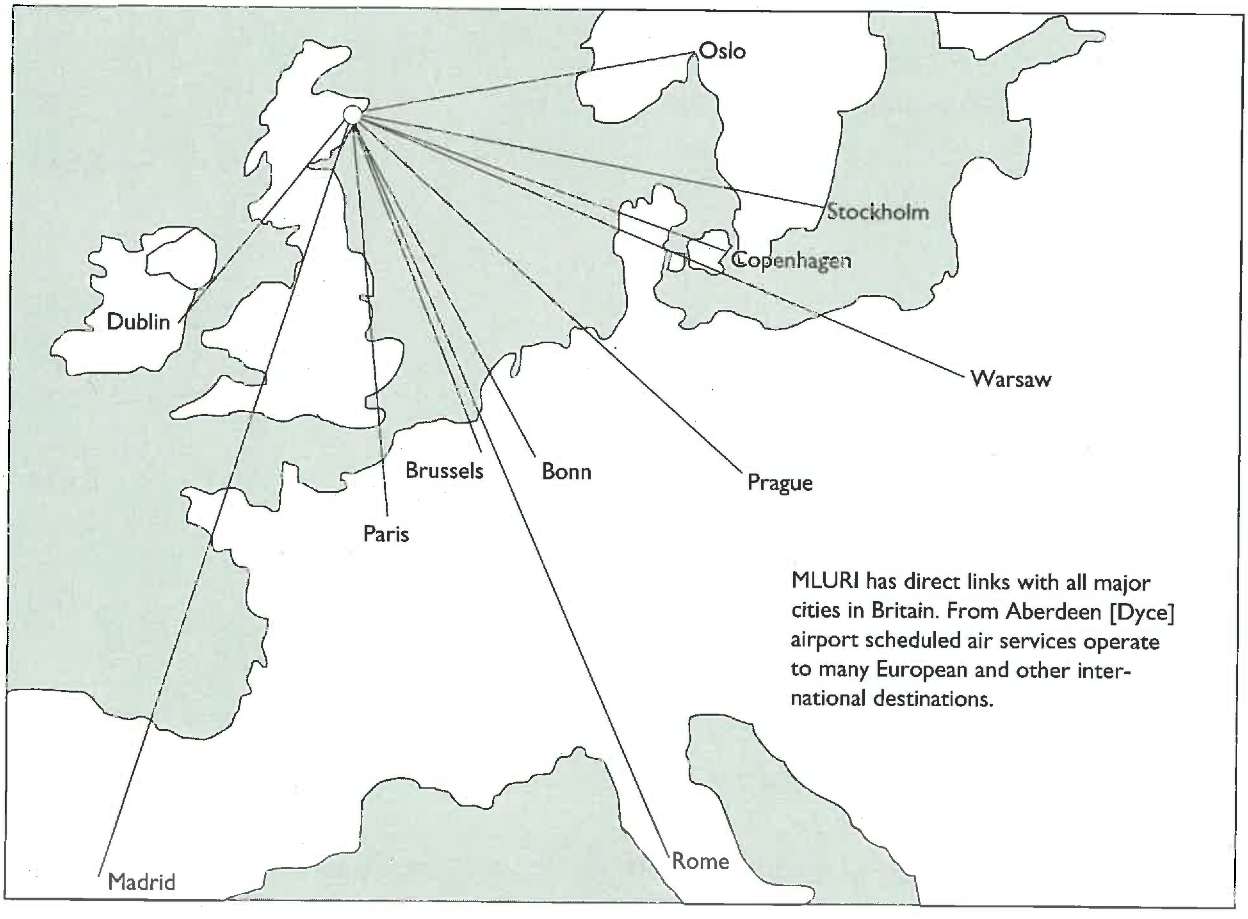
The capital funds received from SOAEFD totalled £595,863 of which £214,113 was for capital works.

During the year the turnover of the Macaulay Research and Consultancy Services was £625,225

MLURI CONNECTIONS



MLURI *is on the east coast of Scotland on the western outskirts of Aberdeen. It is well served by direct British Rail Intercity and Scotrail links. By road from the south the A90 runs directly from the motorway network at Perth. From the north follow the A96 from Inverness.*



MLURI has direct links with all major cities in Britain. From Aberdeen [Dyce] airport scheduled air services operate to many European and other international destinations.

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