Institute of Terrestrial Ecology

Annual Report 1994–95

Centre for Ecology and Hydrology

Natural Environment Research Council

The ITE mission

The Institute of Terrestrial Ecology will develop long-term, multidisciplinary research and exploit new technology to advance the science of terrestrial ecology, leading to a better understanding and quantification of the physical, chemical and biological processes of the land.

Priority is placed on developing and applying knowledge in the following areas:

- the factors which determine the *composition*, *structure*, and *processes* of terrestrial ecosystems, and the *characteristics* of individual plant and animal species

- the dynamics of *interactions* between atmospheric processes, terrestrial ecosystems, soil properties and surface water quality

- the development of a sound scientific basis for *monitoring*, *modelling* and *predicting* environmental trends to assess past, present and future effects of natural and man-made change

- the securing, expansion and dissemination of ecological data to further scientific research and provide the basis for impartial advice on environmental protection, conservation, and the sustainable use of natural resources to governments and industry.

The Institute will provide training of the highest quality, attract commissioned projects, and contribute to international programmes.

ITE will promote the use of research facilities and data to enhance national prosperity and quality of life.

Report of the Institute of Terrestrial Ecology 1994–1995

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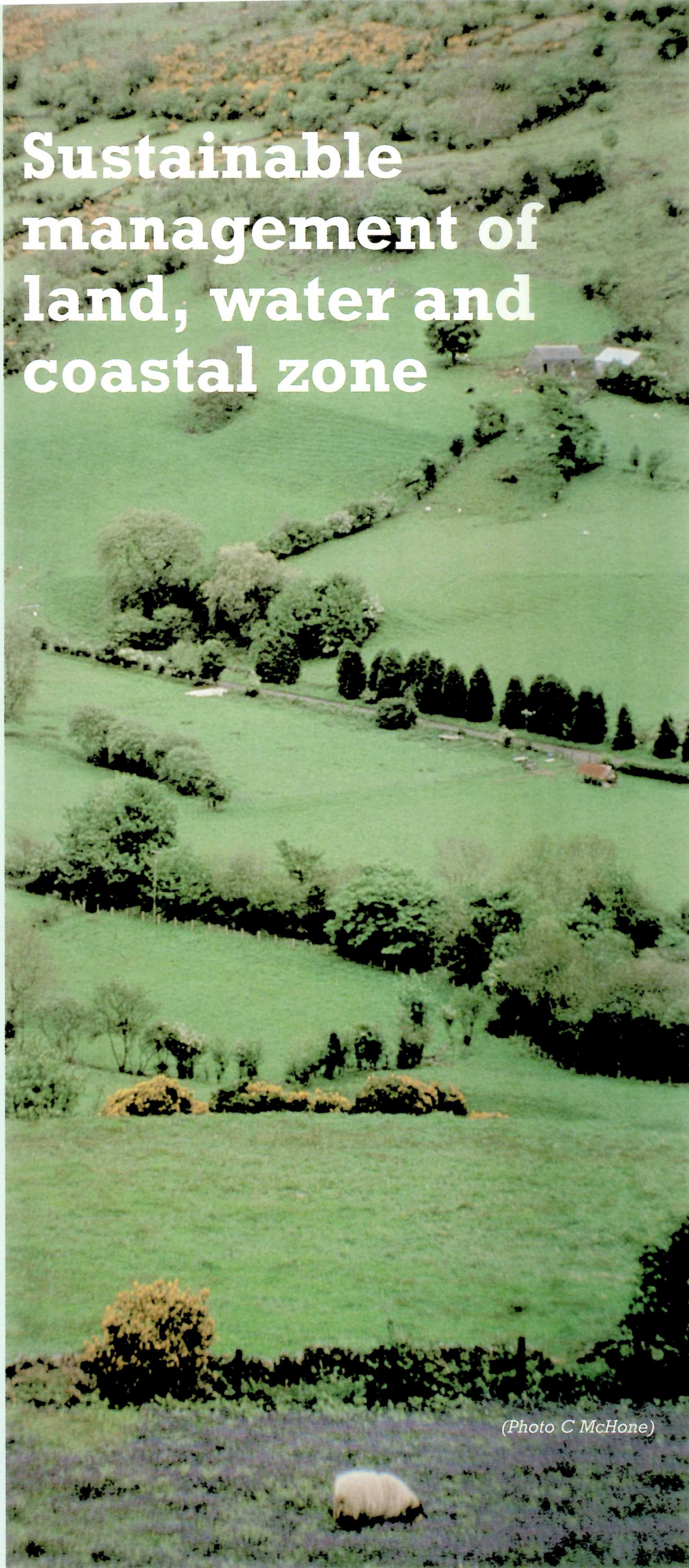
Contents

Science Reports

- Multidisciplinary research on the land/sea interface and the flux of materials from the uplands to the sea and between the atmosphere, land, rivers and seas, leading to better predictive modelling of the response of the coastal zone to change and the development of effective coastal zone management strategies.
- Analysis of physical and biological processes within land-based ecosystems with increased scales of space, time and complexity, to provide a basis for integrating environmental and production criteria in land use planning and management and for studies of the impacts of land use change. Application of hierarchy and biogeography theories to explain landscape-scale dynamics and to develop management techniques that maintain landscape quality.
- Geological, geophysical and geochemical data gathering, interpretation and mapping relevant to the identification and optimum management of land- and marine-based sources of energy and construction materials and to groundwater resource and land use planning issues.
- Multidisciplinary research to understand the processes operating in the urban environment and the environmental consequences of rapidly increasing urbanisation, as a basis for the planning of urban development and renewal and the overall enhancement of the urban environment.
- Underpinning research on the interactions between physical and chemical processes and the productivity of marine- and land-based ecosystems and the implications for the development of renewable resources such as forests and fisheries.

(NERC priorities 1995)

Sustainable management of land, water and coastal zone



(Photo C McHone)

Principal areas of dense shrub heath – derived from the Land Cover Map, summarised at a 1 km square level, and printed from the Countryside Information System

Introduction

In these crowded British Isles, land is precious and it is imperative that, from the highest mountains to the sea coast, whether managed primarily for profit, amenity or wildlife conservation, we use it effectively. In order to manage any resource optimally, it is first necessary to know its nature, extent and distribution. Given the variability in Britain's topography, geology, soils, flora and fauna, some sort of classification is necessary as a first step. Many attempts have been made to classify, survey and map the land of Britain, and ITE has played a key role in this process in recent years, culminating in the production of the various outputs from the Countryside Survey 1990, sponsored by the Department of the Environment (DoE). The survey itself, the land classification it produced, and information on changes in the occurrence and distribution of the different land classes have been described in previous ITE *Annual reports.*

Describing our environment and the changes which are occurring in it, whether due to anthropogenic or natural causes, is of limited value unless that information can be used by those who have to devise and implement land use policy, at the national, regional or local level. In order to aid such decision-making, ITE has developed a user-friendly, Personal Computer-based Countryside Information System which allows information from the 1990 Countryside Survey and earlier ITE land use surveys to be accessed interactively by the user. Based on the 1 km squares of the GB National Grid, the information is being supplemented by the incorporation of other relevant datasets, including data contained in Ordnance Survey maps, leased from the OS. The aim is to produce the most comprehensive information system possible for decision support. More information about the Countryside Information System is given in the first article following this introduction.

As well as being able to access information on current land use and recent land use change, policy-makers and others (landowners, farmers, foresters, wildlife conservationists) involved in rural planning and land management often wish to predict what future changes are likely to take place and how these will impact on their spheres of interest. In order to provide reliable predictions of this kind at any level from the general to the highly specific, it is necessary to have a thorough understanding of the way the system in question functions. The mechanisms involve complex interactions between many factors, often including socio-economic components as well as ecological ones. Unravelling these relationships may take a great deal of time and effort and in many cases is only possible with the help of powerful computers which can readily perform the complex mathematical calculations required. However, even in the intermediate stages of model development when knowledge is imperfect, the ability to predict system response to perturbation is likely to be more precise than beforehand, thus aiding decision-makers. In the articles which follow, examples are given of a range of predictive modelling activities relating to land use, and especially land use change, which have been or are in the process of being developed by ITE.

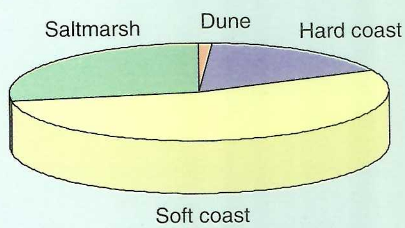
At the general scale, the development of a model is described which attempts to provide an objective cost–benefit assessment of alternative land management strategies taking account of, for example, benefits such as 'human pleasure' and 'species conservation', as well as the more tangible financial benefits arising from the sale of more traditionally marketable commodities. A very different large-scale modelling exercise attempts to simulate the effects of habitat loss on migratory shorebirds. This study has grown out of a much more local study of one species, the oystercatcher, and illustrates the need to set local changes in patterns of species distribution and abundance within a wider regional or even global framework in order to develop accurate predictive models of this kind.

The use of process-based models to describe how a particular type of land use system operates and to predict where, when and in what form it can function sustainably is exemplified by the Agroforestry Modelling Project, which is funded by the Overseas Development Administration and co-ordinated by ITE. The key aim of this study is to understand the mechanisms involved in tree/crop interactions so as to be able to predict where agroforestry may offer benefits. The article indicates the complexity of such mechanisms and the difficulty of developing reliable predictions for particular agroforestry systems. It also highlights the improvement in understanding which occurs in grappling with these problems.

Coming nearer to home, the final article in this section reviews the information available on the effect of fish-eating birds (notably cormorants and sawbill ducks – goosanders and red-breasted mergansers) on freshwater fisheries in Britain. This study was commissioned by the National Rivers Authority because of the growing concern among the owners of freshwater fisheries and anglers that, following the birds' protection under the 1981 Wildlife and Countryside Act, numbers have greatly increased on inland waters and are seriously damaging fish stocks. The authors conclude that there is no unequivocal scientific evidence either to support or refute the charge, and suggest that the reason for this lack of evidence is that good experimental studies are difficult and expensive.

The reports highlight the fact that outputs from predictive models are only as good as the data fed into them permit; the way ahead is to integrate theoretical moelling with the long-term studies required to produce the empirical data.

J E G Good



Proportions of four coastal categories – derived from Countryside Survey 1990

Countryside Information System

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

Countryside Survey 1990 (CS90) was a major survey of the status of the British countryside (Barr *et al.* 1993) and builds on two earlier surveys carried out in 1978 and 1984. The project, partly funded by the Department of the Environment (DoE), was undertaken by ITE and the Institute of Freshwater Ecology. It provides information on the stock and change in landscape features in Great Britain that is necessary for DoE and other Government agencies to help formulate environmentally sensitive policy and identify areas of concern. DoE's experience with other projects undertaken in the 1980s, which investigated changing rural landscapes (eg Huntings Surveys and Consultants Ltd 1986), had proved difficult to assimilate when presented as paper reports and tables. An improvement in the methods of communication was considered essential for CS90 and a more effective and efficient method of access to results was planned using a computer-based system.

The potential of computer technology to provide policy-makers with access to data and assistance in interpretation was explored in the late1980s as part of the Environmental Consequences of Land Use Change (ECOLUC) project, also partly funded by DoE (Bunce *et al.* 1993). Demonstrator systems were developed to show the potential of expert systems, hypertext and information systems. Issues such as identifying the environmental impacts of forestry at the national level and the establishment and management of herb-rich meadows were used as examples. However, discussion and demonstration with the people who need the information, the policy advisors, led to the specification of the system being refined. Of the trial systems developed, the most suitable was a flexible and general information system, which could link easily to other systems available to policy advisors. The prototype, written in Microsoft Windows, was developed in a subsequent project, funded by DoE, and has become the Countryside Information System (CIS) (Howard *et al.* 1994).

Development from the prototype took place between September 1991 and March 1993 with successive modification and periodic review (*cf* Dunn & Harrison 1991). In this way a group of users, the Steering Group, had effective control on system development. The design of the system reflected not only the potential offered by computing, but also the Group's requirements and its level of understanding of the technology; all three developed throughout the project. Throughout the development work the goal has been to create a system which:

- presents the policy advisor with data which describe the rural environment in a way relevant to national policy concerns and which can be correctly interpreted;
- can be used within a realistic timeframe for the normal process of policy appraisal (ie hours or days, rather than weeks or months); and
- requires no specialist training other than that which is expected to use standard modern office computer packages.

CIS was developed using the guidelines set for the development of Windows packages (screen layout, menu structure, command terms and abbreviations) and consequently looks similar to many packages. People who use Windows packages feel they can use CIS intuitively, and information (both maps and tables) can be passed between packages using the clipboard. The system runs on a standard office Personal Computer with Intel processor chips (80386 or better), and is compatible with the range of hardware and software tools normally available to the policy advisor.

One of the features of CIS is its capability of producing distribution maps of the elements in question. The capability often draws comparison with geographical information systems (GIS); although there are now a range of commercial Windows-based GIS packages, none can present and qualify the CS90 data in the same way. CIS is much more of an information system with some spatial capability, and should be judged more on its decision support capability.

In an ideal world, the policy advisor would have access to information covering every aspect of the environment for the whole country at a range of scales. However, such complete (census) data are often unobtainable, expensive or too time-consuming to collect. Sample data can provide the necessary information and need not be less reliable than census information. Indeed, sample data are easier to qualify with measures of accuracy, but the user must be made aware of the appropriateness of different styles of data for different questions. CIS presents both census- and sample-based data, along with descriptions and qualifiers to assist interpretation. The system allows the different data structures

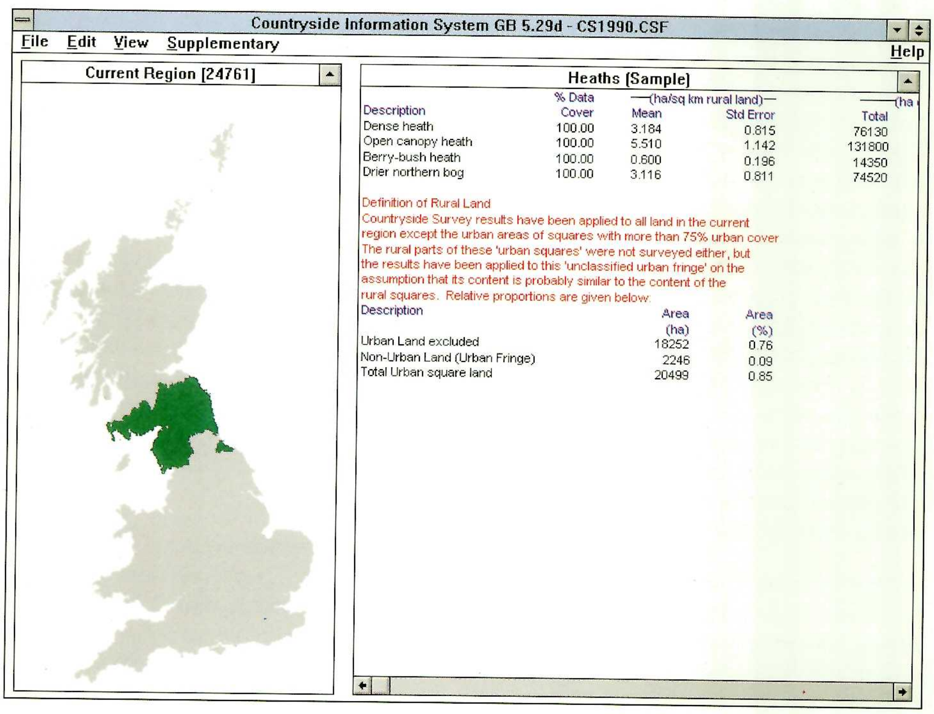


Figure 8. CIS screen showing a selection of counties (identified in the map screen) and the projection of Countryside Survey 1990 field results for heaths for the region

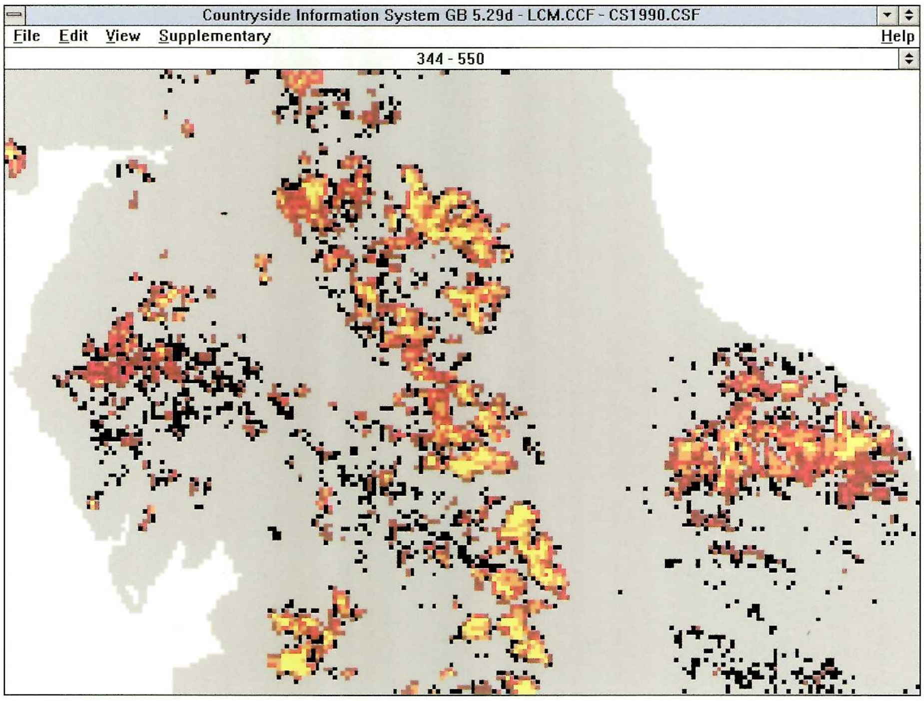


Figure 9. CIS presentation of the Land Cover Map of Great Britain, showing an analysis of dense heath in northern England

(sample and census) to be presented and compared, thus providing a more rounded, integrated description.

Data from the three Countryside Surveys (1978, 1984 and 1990) are held as sample-based information within the CIS. All three surveys were structured using the ITE Land Classification, which was created to provide a sampling framework for national surveys (Bunce *et al.* 1995). The ITE Land Classification uses the 1 km × 1 km cells of the GB National Grid, and these form the basic spatial units on CIS. The Land Classification assigns every 1 km square to one of 32 land classes which serve as a sample stratification for field survey. The land class system conforms to the classical principles of statistical design, in that it reduces sample variability by stratifying a sample according to some of the known underlying characteristics of the population.

For presentation the detailed land cover types mapped in the field have been aggregated into 58 variables considered appropriate for work at the national policy level. They are held on the system as mean and standard error values for each land class. Any geographical area composed of 1 km squares can be selected within the system and will be shown as a map in a window on the screen. The land class distribution of the area is automatically calculated and the number of squares in each land class is multiplied by the average for each feature; the totals are presented in the window next to the map (Figure 8).

A satellite-derived Land Cover Map was also generated within CS90. Although the information was captured and is held at a 25 m pixel resolution, it has been interpreted and summarised at a 1 km square level, dividing land cover into 17 categories. CIS allows the data to be presented and interrogated for different parts of the country (Figures 9 & 10). Care has been taken to ensure that the categories used to report the satellite data not only are relevant in policy terms, but also relate easily to sample-based data available through the field survey component of CS90.

Although the CIS was conceived originally as a means of providing access to CS90 data, as the system developed its potential as a tool for presenting other environmental data available was recognised. Thus, the requirement to hold additional information on the system has been added to the original objectives. The system is capable of holding a range of census-based information at national scales where 1 km squares of the National Grid are used as the basic spatial unit. A dataset leased by NERC and DoE from the Ordnance Survey describing land cover features, such as altitude, roads, buildings, lakes and woodland, is now available in CIS format. Other datasets are also being prepared for inclusion in CIS and cover a wide range of topics.

CIS is now commercially available under agreement with DoE, being marketed by NERC and supplied by the Software Development Section of the Institute of Hydrology. Yvonne Parks should be

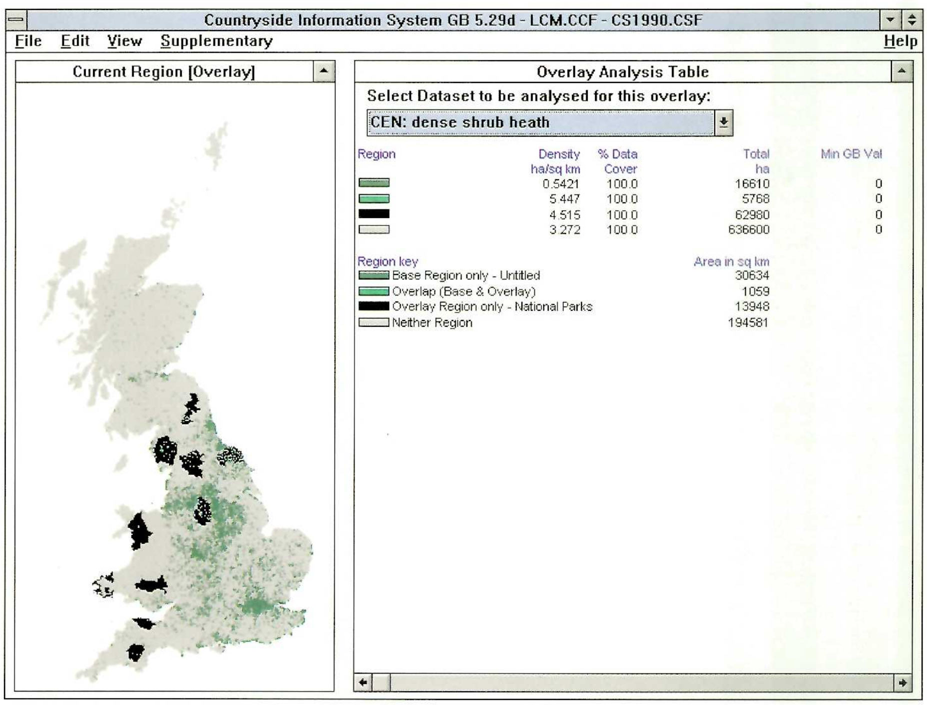


Figure 10. CIS presentation of a selection from the Land Cover Map of Great Britain (urban land) overlayed with National Parks

contacted for further details. Datasets will also be available, advertised on the system in an environmental catalogue which identifies points of contact. Work to extend the system is continuing under a new contract for DoE, entitlted Access to Data and Dissemination Services (ADDS).

R G H Bunce, D C Howard and J W Watkins

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Decision modelling: land use policy evaluation

(This work was partly funded by the Scottish Office)

A difficulty when making decisions about complex issues, such as land use, is that the human mind cannot entertain more than about seven points at the same time (Fechner 1860). The information available is always incomplete, varying in reliability from hard facts to unsubstantiated intuitions. And, generally, there are conflicts of interest, so that conclusions involve compromises between different viewpoints.

Plate 7. The Dee valley west of Kincardine O' Neil, showing the type of landscape in which the pilot study was done

'Harmony is a blending and combination of opposites' (Aristotle 384–322 BC)

Such complexity offers opportunities for skilful advocates to press for the interest groups which they represent. Alternatively, we report here how decision theory can provide an objective and transparent basis for reaching consensual decisions. ITE has developed a quantitative and transparent system for integrating available information into decisions about land use, and an impartial mechanism for generating compromises between divergent interest groups.

Approach

The approach adopted examined the costs and benefits of alternative land uses, both separately and in combination. Costs and benefits can be financial, social or ecological, involving aesthetic and ethical as well as financial considerations. Rather than attempting to convert spiritual values into financial ones, we chose a psychometric modelling technique based on decision theory, using 'strength of expert opinion' as currency.

A computer model has been developed that is a general tool for integrating all types of available information into predictions about the likely costs and benefits of a range of alternative management strategies. It is a general framework for making policy decisions and has the following characteristics.

- All relevant issues are given due weight.
- Time is not wasted on irrelevant matters or personal antipathies.
- Accurate records are kept of the issues considered and the weight given to them.
- Input is allowed from knowledgeable people who are not necessarily fluent in the niceties of committee room debate.
- An impartial mechanism is provided for recording and resolving conflicts of interest quickly and with minimum friction.
- The consequences of varying the weight given to each issue can be ascertained quickly and simply.
- It is quantitative, allowing input in any currency (eg money, measurements of any sort, good, pleasure, etc).
- The end product is a cost score and a benefit score for each of the management strategies considered. The mechanism by which these scores are reached is recorded. The scores can be disaggregated to see what created them, and input can readily be altered to see the effect on the scores and the overall robustness of any conclusions.

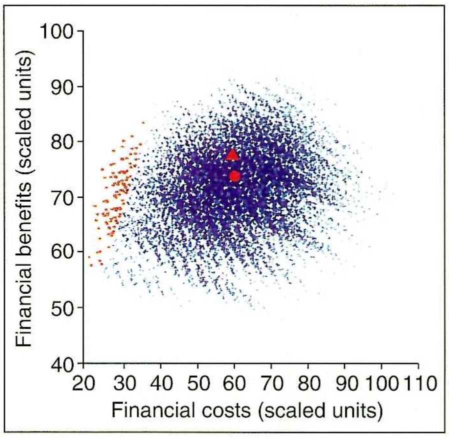

Figure 11. Scatter diagram, from the pilot study, of financial costs and benefits for each strategy. The position of the current management strategy is marked as a red circle and the position of a new strategy, about to be implemented, as a red triangle. Red dots show the position of the 100 highest scoring strategies by ratio of benefit to cost. There are 9450 packages in total

The modelling method

The method is based on a decision conferencing procedure described by Phillips (1989).

- The ground is divided into n classes according to its main use: forest, moor, farm, and so on.
- A number of options for managing each ground class is decided upon. A management strategy or 'package' thus comprises a set of n options, one from each ground class.
- The overall costs and benefits for each option are assessed from a number of criteria. Cost criteria, for example, might include monetary running costs and pollution; benefit criteria might include income and spiritual growth.
- An expert panel assesses each criterion on an interval scale of 0–100: 0 is the worst possible realistic situation for the criterion being considered, 100 the best.
- The scores are weighted and normalised using techniques from multi-attribute utility theory (Edwards & Newman 1982).
- The overall cost and benefit of each management package is calculated.

The 'value' of an option can be operationally defined as its benefit/cost ratio, but cost and benefit scores can, in principle, be analysed in any way appropriate. Different interest groups have different opinions about the costs and benefits of each option and use different criteria to assess them. An impartial mechanism for resolving conflicts quickly and with minimum friction has been developed. Different interest groups with distinct and different priorities are identified and separate models built with each group. Each model has the same options but may have different criteria. A compromise set of packages is identified as follows.

The list of packages from each model is ranked according to value. One then runs down each ranked set of packages and stops when there are, say, 100 'compromise' packages in common. These compromise packages then form the basis for discussion between the interest groups.

The pilot study

The study (Moss, Catt & Bayfield 1994) involved developing criteria for sustainable land use on an upland Scottish estate which included five land use classes: forest, moorland, farms, rivers and lochs, and buildings and roads (Plate 7). Three different perspectives were modelled, one involving primarily financial matters, one social aspects, and one ecological considerations. These three perspectives were then integrated in a 'compromise' model.

The three separate analyses using, respectively, financial, social and ecological criteria for assessing costs and benefits led to different rankings for the values of different management packages, and a compromise set of packages was identified and compared with current management.

Results

Figure 11, from the pilot study, shows the overall financial costs for each package plotted against its overall financial benefits. The 100 packages accorded most value (red dots) by this financial analysis all involved reduced costs relative to the *status quo* (red circle). This suggested that more profit could be made by reducing costs. Although most (70%) of these packages also had reduced benefits, some (30%) involved similar or improved benefits.

However, similar plots from the social and ecological analyses gave different results. The 100 most valued social and ecological packages showed little overlap with each other and even less with the financial analysis. This result represented conflicts of interest between different viewpoints.

The favoured options in each of the three models were discovered by disaggregating the top 100 packages.

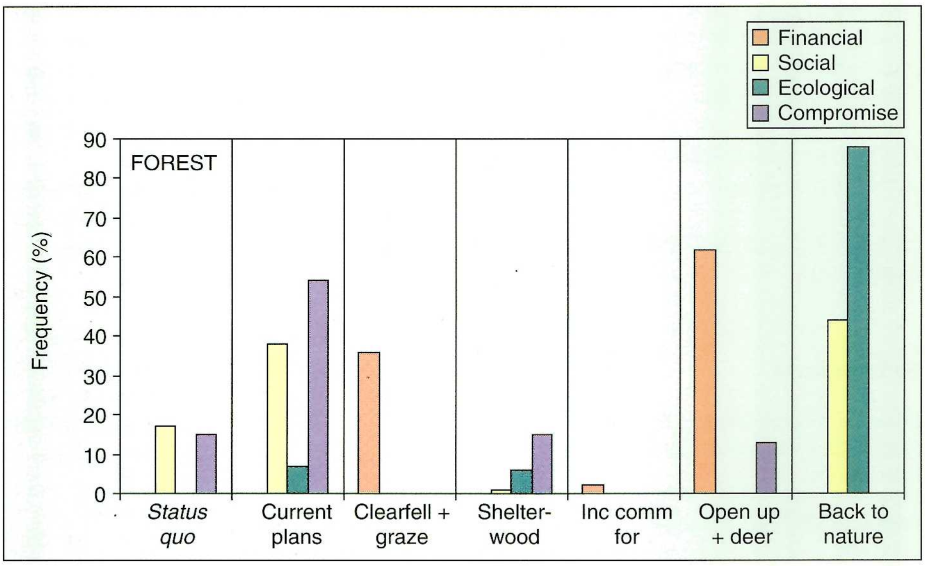

Figure 12. Frequency of various options in the top value 100 financial, social, ecological and compromise packages for one land use class (forest)
The options included: *Status quo* – current management; *Current plans* – includes planned changes in management; *Clearfell + graze* – clearfell the forest and convert to grazing; *Shelterwood* – change forest management to a shelterwood system; *Inc comm for* – increase commercially driven forest practices; *Open up + deer* – open up the forest to more red deer by removing fences; *Back to nature* – restore Caledonian pinewood including large mammals. Two options (*Increased commercial recreation* involving visitors paying for access, war games, etc, and *Increased non-paying recreation* involving an increase in the present trend to more visitors) did not occur in the top 100 packages and so are not included in the Figure

The frequency with which each option occurred in the 100 most valued packages was used to indicate the most favoured options. Figure 12 shows results from the pilot study and illustrates the conflicts between viewpoints. The 'compromise' set of options involved running down the three lists of packages ranked according to their financial, social and ecological values and stopping when there were 100 compromise packages in common. In the pilot study, this involved the top 20% from each of the three lists (Figure 12).

Discussion

The expected consequences of alternative policies can be modelled to show, for example, how a change in fiscal policy can have a major effect on land use. It is not suggested that decision-makers should rely upon such models to make decisions for them – they are simply aids which ensure that full consideration has been given to most relevant factors and enables one to compare a large number of alternative ways forward. The input provides a numerical record of exactly how the conclusions were reached. If new information arises or management objectives change, the model can be run again. The modelling process itself, as distinct from the model output, was a learning process for all participants, who developed a shared understanding of the problems and a new appreciation of each others' points of view.

A Windows-based version of the software is being developed.

R Moss, D C Catt, N G Bayfield and D D French

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The large-scale approach to modelling the effects of habitat loss on migratory shorebirds

(This work was funded by the Joint Nature Conservation Committee)

In autumn, many hundreds of thousands of waterfowl and waders come to Britain from more northern areas. For many species, the numbers that visit Britain constitute a substantial proportion of the total East-Atlantic Flyway, or even world, populations. Britain has an obligation under international agreements, such as the Ramsar Convention, to protect these birds and their habitats. Predicting the effects of different types of habitat change on the size of populations of these migratory birds is of critical importance if management strategies are to have a sound scientific basis.

Goss-Custard *et al.* (1993, 1995a) have shown that the effect of a given loss of overwintering habitat is influenced by the strength of the overwinter, density-dependent mortality function. Therefore, we need to estimate the form of such functions if reliable predictions are to be obtained. Our approach has been to develop an empirical, individual-based model that generates the critical overwinter, density-dependent mortality function by simulating foraging birds and 'killing' those that fail to achieve the intake rate required to survive.

The original version of this model was built on the results of 15 years of field studies on oystercatchers (*Haematopus ostralegus*) feeding on the mussel (*Mytilus edulis*) beds on the Exe estuary (Goss-Custard *et al.* 1995a,b) (Plate 8). Predicting the effects of the loss of overwinter habitat of average quality on the global population of oystercatchers could be achieved by including the density-dependent mortality function, derived from the within-Exe model, in a demographic model of the global population. To do so would make two assumptions. First, that the form of the density-dependent mortality function, as determined from the model of the Exe estuary, applies to all estuaries, thus assuming they are of the same 'average' quality as the Exe. Second, that individuals which fail to achieve the intake rate required to survive on their chosen site choose to remain there and starve, rather than leave in search of an alternative. To avoid making these assumptions, it is necessary to consider a truly large spatial scale. Thus, we have extended our modelling approach from dealing simply with patterns of distribution within a single site to consider the movement and distribution of birds between any number of sites that vary in quality and which may be thousands of kilometres apart in a spatially explicit model world.

As in earlier versions of the model (Goss-Custard *et al.* 1993, 1995a,b), the basis of the new model is the calculation of the rate at which individual birds feed. This rate depends upon a bird's foraging efficiency in the absence of other birds of the same species (conspecifics), the quality of the site, the density of neighbouring conspecifics and the bird's susceptibility to interference from these neighbours. The last of these factors depends on an individual's fighting ability relative to its local competitors. In the current model, an individual's intake rate is used in conjunction with its rate of energy expenditure to determine its body condition (ie proportion of its total mass that consists of fuel reserves). The decision to leave a site and go to another

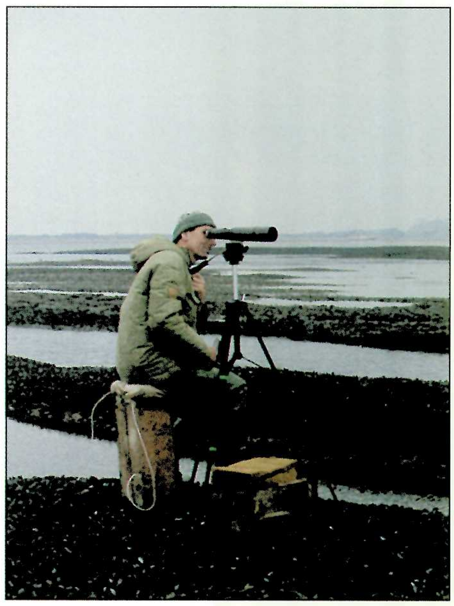

Plate 8. Carrying out behavioural observations on oystercatchers foraging on a mussel bed in the Exe estuary. The results of many years of such observations enabled parameterisation of the first individual-based, within-estuary model of oystercatcher distribution

depends entirely on this factor and is made according to a few simple decision rules derived from empirical studies of the factors controlling bird migration. In the light of empirical studies, the model assumes that there are two phases of bird migration. First, there is an obligate phase in which individuals are obliged to leave sites by their migratory urge to reach a distant goal, even if they can sustain themselves on their current site. Second, there is a facultative phase which birds enter once they have reached their migratory goal. Once in this state, individuals leave a site only if they cannot sustain themselves upon it. Once flying, birds in these two migratory phases also decide when to settle on a site according to different decision rules. The decision rules relating to departure from and settlement on sites are depicted in Figure 13.

The model simulates a two-dimensional model world. This world is divided into a number of non-overlapping climatic zones within which the temperature and wind strength and direction are determined on a daily basis. There are also functional zones in the world that define the boundaries within which all the sites must lie. Each site is given an x and y co-ordinate and is classified as a breeding, staging or wintering site, depending upon within which functional zone it falls. The model tracks the intake rate and body condition of each individual. Birds move around between sites according to their body condition, migratory status and the simple decision rules. The model tracks the location in space of all birds at all times as they migrate between the breeding and wintering grounds each year. Individuals can die because of starvation on a site or as a result of running out of fuel while *en route* from one site to another.

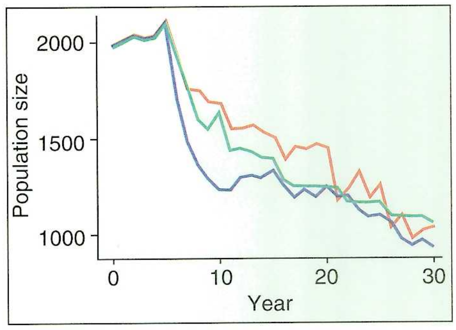

Figure 14. The pattern of change of the total population size at the end of each successive breeding season as 10% of the winter habitat is removed progressively every fifth year.
The red line is the habitat removed progressively from all winter sites equally; blue is habitat removed progressively by destroying the southernmost wintering site at each step; green is habitat removed progressively by destroying the northernmost wintering site at each step

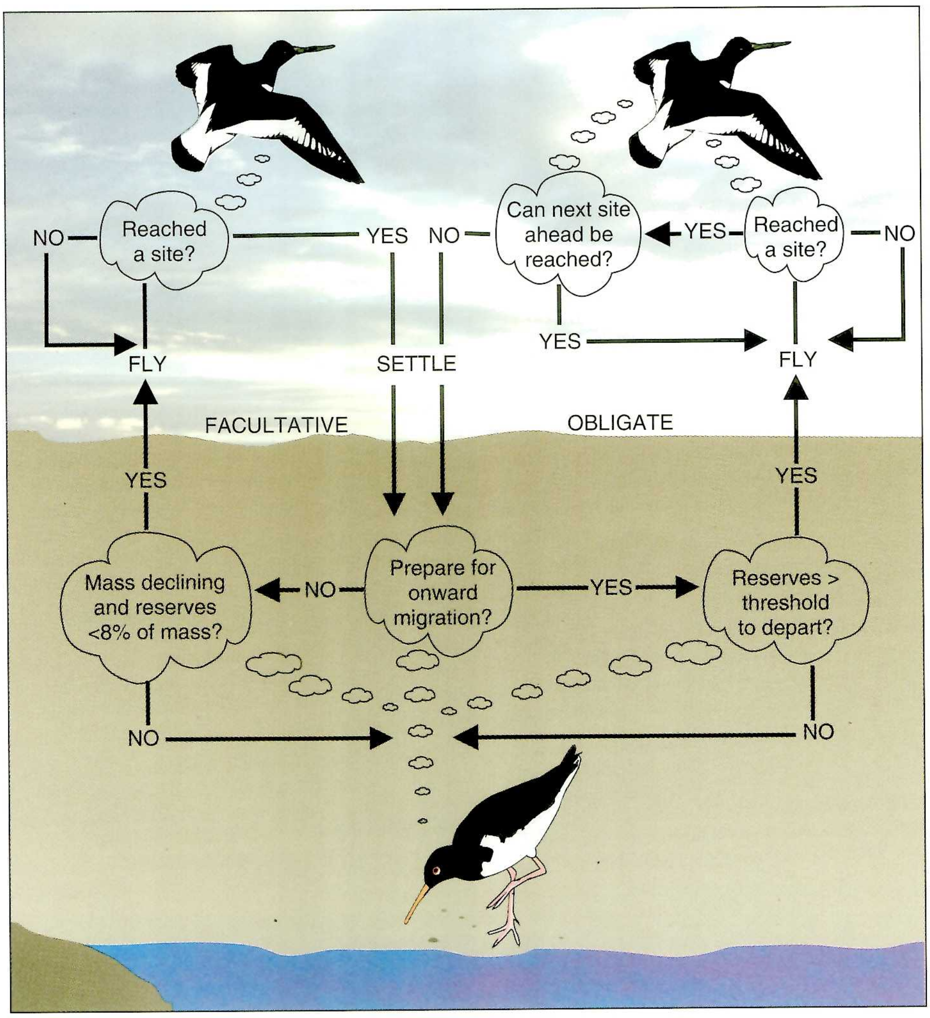

Figure 13. Schematic representation of the rules followed by birds when deciding whether to leave or stay on a site and whether to settle on a site or continue flying. Birds in the facultative phase leave a site only if they cannot sustain themselves on it, and land again on the first site that they reach. Birds in the obligate phase depart only once they have sufficient reserves to ensure a safe passage at least as far as the nearest site on their route. They will, however, overfly this site and continue flying to the next site ahead of them, if this can also be reached safely

The first runs of the model have been carried out to predict the effects of the progressive loss of winter habitat on the population of a species, like the oystercatcher, that exhibits intense interference competition. Habitat was removed in one of two ways: by removing an equal area from each wintering site or by progressively removing entire sites to give the same gradual reduction in total area. In the latter case, sites were removed in latitudinal order, starting either with the southernmost or the northernmost wintering site. In all three cases the progressive loss of habitat was simulated by removal of 10% of the original total area of winter habitat at the end of every fifth year.

As can be seen in Figure 14, the progressive loss of winter habitat results in a decline in the size of the population that can be sustained. However, the model shows that the population trajectory varies according to the pattern of habitat loss. The reduction in the population size occurs more rapidly in response to habitat loss when entire sites are removed than when the same total area of habitat is removed across all the winter sites. This is especially so if the sites removed are the more southern ones. Initially, the reduction in the population is supra-proportional – that is, the percentage reduction in population size is greater than the percentage reduction in the area of habitat. However, as more habitat is

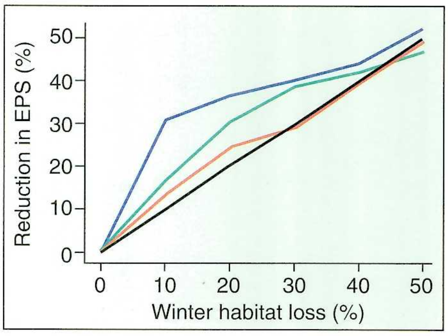

Figure 15. The percentage reduction in equilibrium population size as a function of the progressive loss of winter habitat. The line of y = x (black) is the line of proportionality. Key to lines as in Figure 14

removed, the reduction in population size returns to proportionality (Figure 15).

The model can also generate a number of other predictions of the effects of habitat loss. For example, the removal of southern wintering sites resulted in an advance of up to two weeks in the date of the last departure on spring migration (Figure 16). This advance was not simply a result of the longest migratory distance being shortened by the loss of the sites furthest from the breeding grounds. The advance in the date of the last departure was greatest when the population was at its smallest relative to the area of habitat available, and declined with the loss of further southern sites and as the population decline returned to proportionality. This finding suggests that changes in the intensity of intraspecific competition for food resources are likely to have been the cause of the observed shift in the migration schedule. Because the timing of arrival on the breeding grounds is likely to influence subsequent reproductive success (Ens, Piersma & Tinbergen 1994), the model's ability to

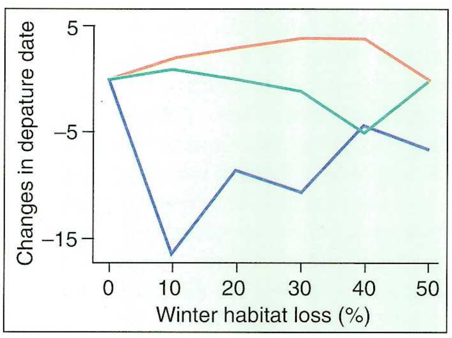

Figure 16. The effect of increasing loss of winter habitat on the number of days by which the date of the last departure on spring migration from the wintering grounds was advanced or retarded. Key to lines as in Figure 14

Plate 9. Brent geese foraging in a flock on grassland neighbouring the Exe estuary. Unlike oystercatchers feeding on mussel beds, this species feeds in compact, fast-moving flocks when foraging on grassland. To reach the Exe estuary from their Siberian breeding grounds, these birds have to fly approximately 5000 km

yield such predictions will be important in identifying the mechanisms that drive the population level consequences of habitat change.

Further versions of the model will be parameterised for a range of migratory species with different foraging and migratory systems. For example, brent geese (*Branta bernicla*) (Plate 9) would provide an example of a system in which the lengthy annual migration is carried out in a few long flights and interference competition is relatively weak.

The model will allow us to compare the response of populations of different species to given environmental changes. As each of the different versions will be parameterised as far as possible from empirical sources and be based on fundamental properties of the birds' behaviour, this type of model should provide a starting point for making quantitative predictions of the effects of habitat deterioration, loss and fragmentation on global populations of long-distance migrant waders and waterfowl. The generation of such predictions will be of great value in developing the scientific basis that must underpin species' management strategies.

R W G Caldow and J D Goss-Custard

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Application of models to tropical agroforestry

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

Growing trees with crops may increase the overall crop yield, and make it more sustainable, but the reverse is often true. The benefits to soil fertility of spreading a mulch of tree leaves are often negated by competition between trees and crops for water and nutrients. Shade can be

Plate 10. Taungya farmer from Mbalmayo, Cameroon, standing beside a young *Triplochiton scleroxylon* tree in an area which she has cleared for planting with groundnuts, maize, cocoyam and cassava. If well managed, this method of plantation establishment can bring benefits to both the forester and the farmer

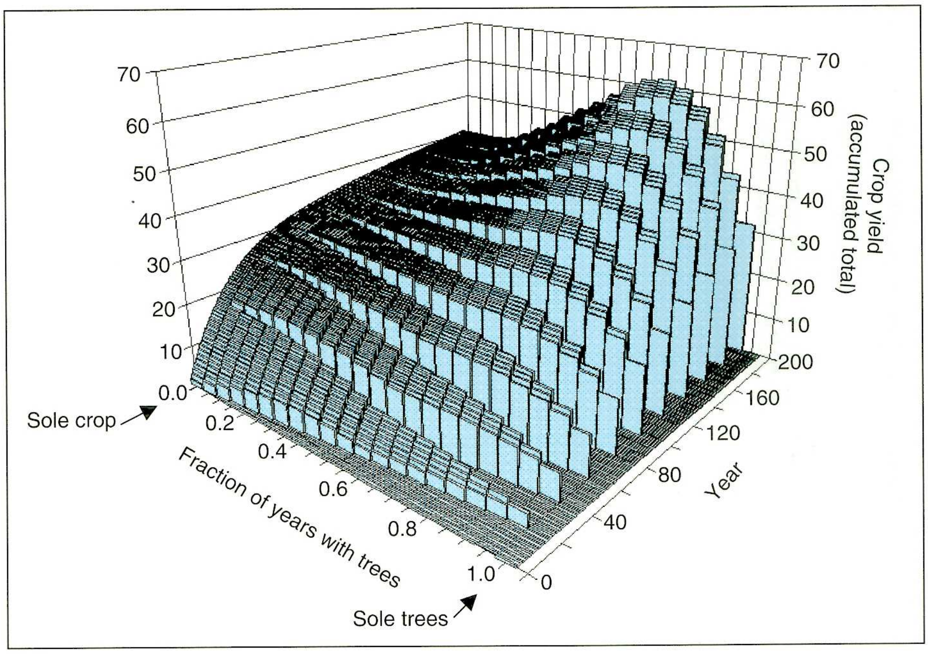

Figure 17. Output from the Rotate acacia/sorghum rotational fallows model, showing accumulated yield of sorghum over a 200-year period, assuming a 20-year tree/crop cycle and different fractions of the 20 years under trees. Tree growth is determined empirically and crop yield is predicted from available soil nitrogen levels. Nitrogen is accumulated under trees and subsequently exploited by annual crops of sorghum The model predicts the rotation length and balance of trees and crops necessary for maximum accumulated crop yield. In this example, maximum long-term crop yield is obtained with about 60% of the 20-year period under trees. Rotate has a useful teaching role in exploring the sensitivity of long-term yield to key variables (eg tree spacing) or parameters (eg decomposition rate of leaf litter)

tolerated by some crops, but not others. Pruning the lower branches of trees causes a small reduction in timber yield, but it increases the light and moisture available to the crops. A particular type of agroforestry may succeed in one area, and fail in another with different soil and climate. Above- and below-ground interactions are clearly complex and difficult to predict, but our understanding can be much increased by developing models of the biological, chemical and physical *processes* involved in agroforestry. This is the task of the ODA Agroforestry Modelling Project (AMP), funded by the ODA Forestry Research Programme (FRP), with the following objectives:

- to evaluate and utilise existing models to understand the mechanisms involved in tree/crop interactions, and to identify those situations where agroforestry may offer benefits;
- to evaluate existing FRP-sponsored field experiments with respect to tree/crop interactions, their conceptual frameworks, measurement protocols and ranges known for different variables.

Several approaches to agroforestry modelling (Plates 10 & 11) have been followed:

- development of a model of rotational fallows of acacia and sorghum, where the optimum rotation length and balance of trees and crops are calculated from measurements of tree growth, litter decomposition and

Plate 11. A semi-arid tropical agroforestry system, near Hyderabad in India, consisting of *Leucaena leucocephala* trees dispersed in a crop of pearl millet. This trial evaluates the effects of tree spacing and pruning on millet production, and examines competition for resources between the two species

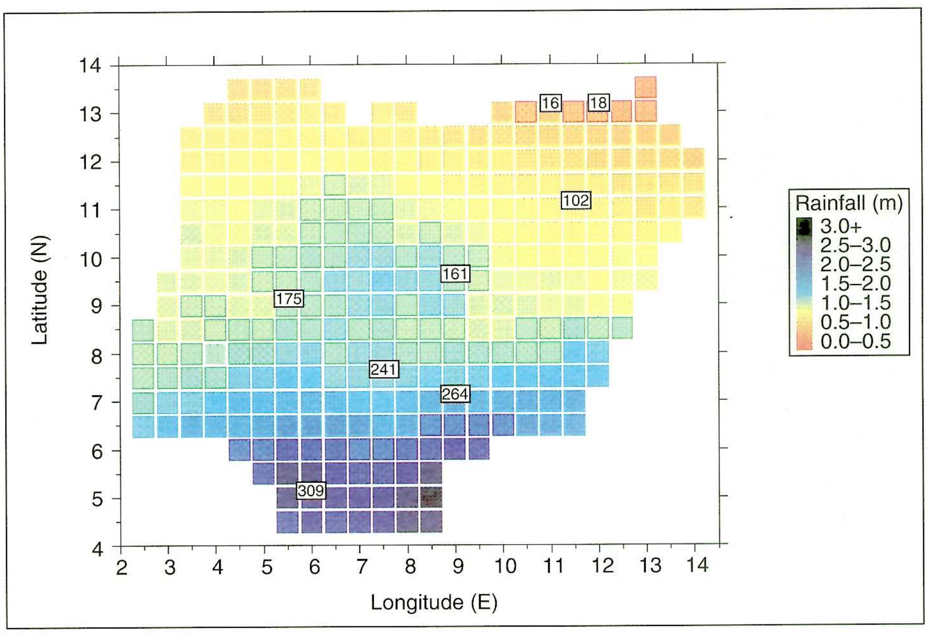

Figure 18. Thirty-year average rainfall distributions in Nigeria. Measured monthly means of meteorological data are extrapolated using a weather generator (Friend 1995), to predict daily means of precipitation, solar radiation, maximum and minimum temperature, and humidity. The eight numbered squares are those chosen for more detailed analysis of potential agroforestry yields

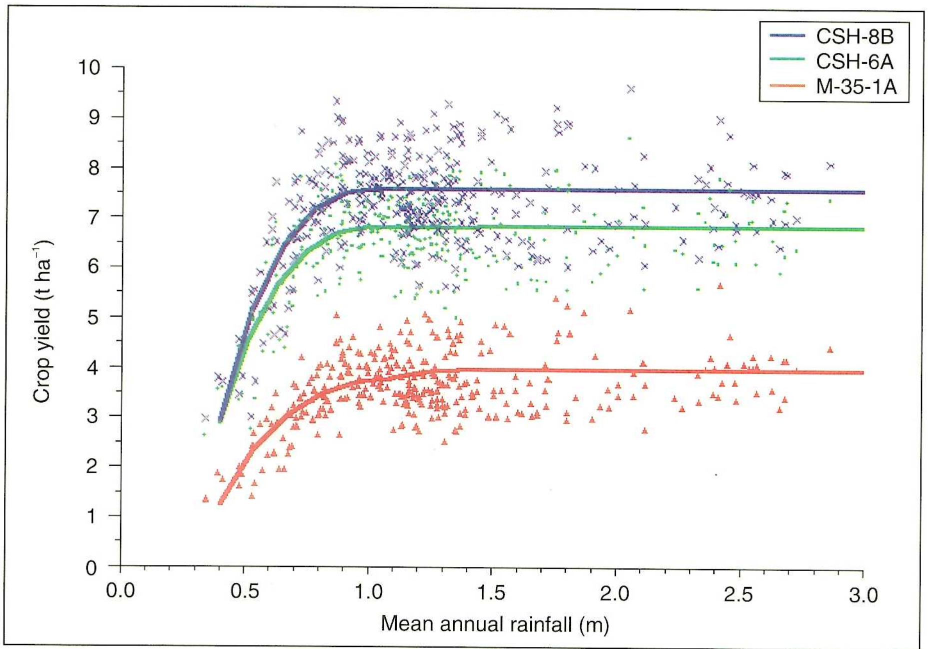

Figure 19. Yields of three sorghum varieties for 321 half-degree squares in Nigeria. Yields are means of 30-year simulations. CSH 6A and CSH-8B are modern semi-dwarf varieties with a high harvest index and reasonable drought tolerance. M-35-1A is an older tall variety with low harvest index. This is output from the PARCH component of the HyPAR model, assuming identical soil conditions in each square. PARCH is a model of crop production in arid environments developed by the Tropical Crops Unit of the University of Nottingham (for parameterisation information, see Bradley, Crout & Azam-Ali 1995)

nitrogen cycling in Senegal (Figure 17) (Mobbs & Cannell 1995);

- coupling of the Hurley Pasture Model with the Edinburgh Forest Model (Thornley & Cannell 1994);
- coupling of existing forest canopy (Hybrid) and crop (PARCH) models, to enable predictions to be made over long periods and wide areas (Lawson *et al.* 1995);
- linking a 3-D tree photosynthesis and light interception model (MAESTRO) with a crop growth model (PARCH), to enable short-term spatial interactions between trees and crops to be examined in detail around individual trees (Levy 1995);
- development (by the Institute of Hydrology – Wallace 1995) of light interception and energy combination theory to describe the partitioning of energy between sensible heat and evaporation in plant mixtures.

PARCH has been translated from BASIC to FORTRAN and combined with Hybrid so that the trees and crops compete for light and water on a daily timescale. The integrated agroforestry model is called HyPAR, and has been used on a regional scale with 30 years of generated daily weather data for 321 half-degree squares in Nigeria (Figure 18). Without trees, it is effectively the PARCH model, and can be used to test the likely yield of different sorghum varieties over the whole country (Figure 19). Once trees are added, the options for agroforestry in different soil and climate types can be explored.

Using 30-year runs of weather at five worldwide sites with different rainfall levels, preliminary studies have investigated the importance of light and water competition in reducing crop yields in tree/crop mixtures. At the wetter sites (Figure 20), shade was clearly the limiting factor on yield, and competition for water

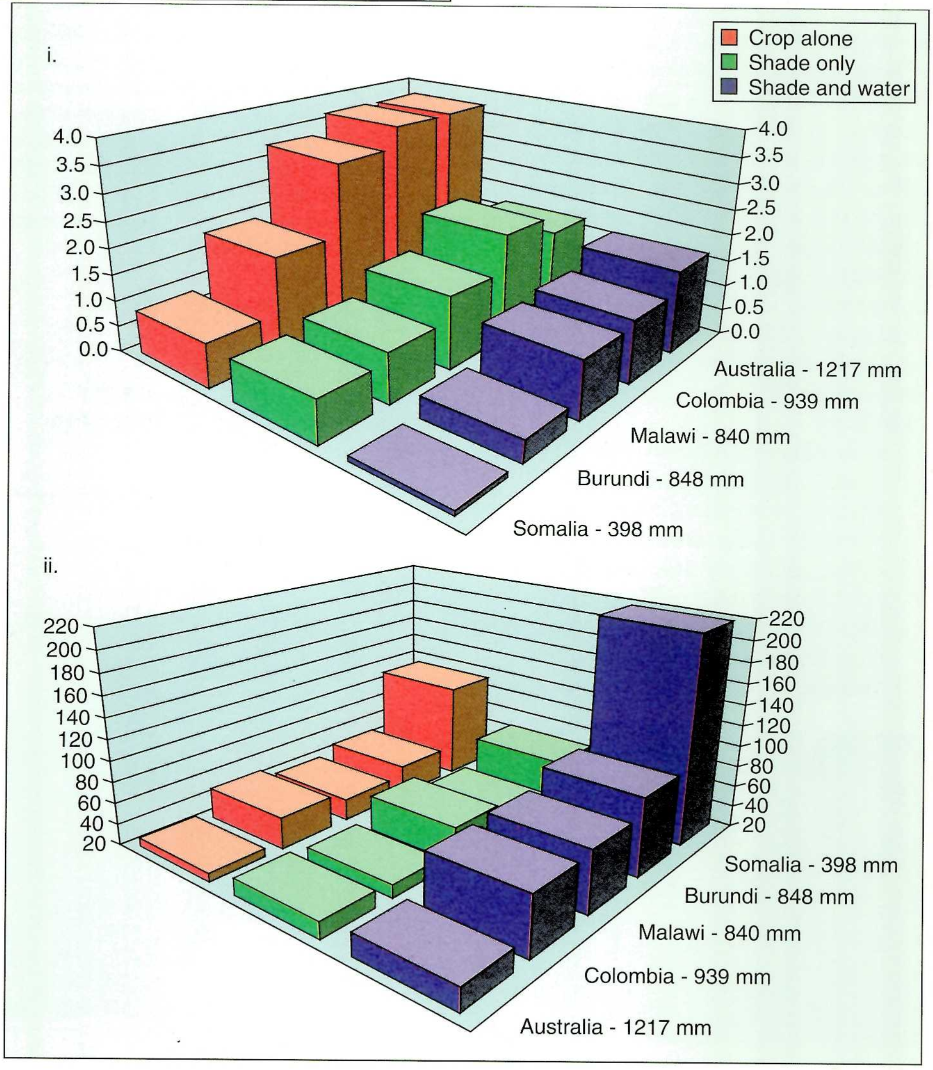

Figure 20i. Hybrid/PARCH simulations of the effect of rainfall and tree competition on the yield of understorey sorghum for five typical sites. Root growth and water availability to crop roots are influenced by soil texture and bulk density but, for comparative purposes, this Figure assumes that soil type is constant for each site and depth layer. The tree canopy has a Leaf Area Index of 1
ii. Hybrid/PARCH simulations of the effect of shade (LAI 1) and water competition on the variability of understorey sorghum yield for the five sites

had little effect However, the driest site shows that shade alone has no effect on yield, but water competition causes crop failure in most years Year-to-year variability in crop yield is increased by introducing trees, particularly at the driest site

A sophisticated 3-D tree canopy model (MAESTRO) has also been coupled with PARCH It produced similar yield predictions to HyPAR, except in very dry conditions where modest yields were projected in areas not occupied by tree roots, whilst the 1-D approximations in HyPAR predicted total crop failure Both Hybrid and PARCH contain nutrient submodels, but these are not yet linked

A second phase of AMP starts in July 1995, involving the following collaborative activities

- continuing the development of HyPAR as a 3-D integrated light, carbon, nutrient and water agroforestry model (ITE and University of Nottingham),
- rewriting the MAESTRO model to make it compatible with other modules in the AMP (University of Edinburgh),
- developing a modular modelling environment to link alternative modules with different levels of complexity (University of Edinburgh and ITE),
- improving the root growth and nutrient uptake modules (University of Reading, ITE, and University of Nottingham),
- improving the modelling of humidity interactions between tree and crop layers (IH),
- interfacing with socio-economic models (University College of North Wales (UCNW) and ITE),
- validation and extension (ITE, the International Institute for Tropical Agriculture, the International Centre for Research on Agroforestry, and UCNW)

G J Lawson, D C Mobbs and M G R Cannell

Acknowledgments

Phase I of the Agroforestry Modelling Project links ITE Edinburgh, the Institute of Hydrology, and the Universities of Nottingham, Edinburgh and Reading UCNW is joining in Phase II

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Do fish-eating birds seriously damage freshwater fisheries?

(This overview stems from a review commissioned by the National Rivers Authority, and is supported with data from research funded by the Scottish Office Agriculture and Fisheries Department)

In Britain, fish-eating birds such as cormorants (*Phalacrocorax carbo*) and sawbill ducks – goosanders (*Mergus merganser*) (Plate 12) and red-breasted mergansers (*Mergus serrator*) (Plate 13) – are widely perceived as damaging to freshwater fisheries, particularly in recent years as their range has expanded and they have become more abundant Formerly these birds were killed wherever and whenever fisheries managers saw fit but, with the Wildlife and Countryside Act 1981, the birds were given protection, with the proviso that licences may be issued to kill them to prevent 'serious damage' to fisheries This has generated controversy because licences have been issued to kill birds merely where it was thought that they were eating large numbers of fish of commercial interest Bird protectionists have argued that such licensing is unwarranted because there is insufficient information to show that these birds are actually damaging fisheries The issue is further complicated because it is not clear from the 1981 Act what constitutes 'serious' damage

In a recently commissioned review (Marquiss & Carss 1994), ITE examined the available information and concluded that there was no unequivocal scientific evidence that birds damage fisheries Many studies had produced anecdotal and circumstantial evidence but none were conclusive This was not necessarily because birds do not affect fisheries, rather it was because there were few experimental studies and these were poorly designed without adequate controls, poorly implemented and not replicated This situation largely reflects the difficulty of the studies required, and the expense and financial commitment involved in large-scale and long-term field experiments

The situation is not, however, totally intractable Where there is claimed to be a bird problem, a stepwise logical approach can be informative The first question to be addressed is whether the fishery has suffered real loss If the licence applicant has not measured fish catches per unit effort, the claim can be dismissed as unsubstantiated Alternatively, if fish catches can be shown to have declined, the next question is whether or not the birds are taking the commercial fish involved An estimate of bird diet sometimes shows this is not the case and, again, the claim can be dismissed Where birds are eating fish of commercial concern, we need to know whether the levels of consumption are consistent with fishery losses Such a calculation involves estimates of foraging bird abundance at the site and their food intake, as well as diet The variation in these estimates needs to be known because the calculation of consumption will have a measure of accuracy (confidence intervals) associated with such variation

Plate 12. A group of goosanders fishing on the River Don, Scotland (photo A Youngson)

If the birds consume large fish, it is possible they are in direct competition with the fishery, and an estimate of the size of the fish population is necessary to provide context. The removal of birds can at best only increase fishery harvest by a proportion equivalent to the proportion of the fish population that the birds consume. If there is no good estimate of the fish population, the potential gain to fishery harvest cannot be calculated. If small fish are taken by birds, even more information is required because we need to quantify how losses of small fish affect the numbers of larger fish, and thus the potential fishery harvest.

Each stage in this sequential approach requires additional information and, as it proceeds, the developing model becomes more complicated. The final quantitative prediction is subject to error associated with the accuracy of each of the measured parameters and the assumptions involved in the interrelationships between parameters. The only way to test whether such a model mimics reality is by controlled experiments.

Plate 13. A male red-breasted merganser (photo R T Smith)

In Scotland, catches of adult salmon (*Salmo salar*) have declined. Catch statistics are notoriously difficult to interpret because catch methods have changed over time, catching effort is difficult to quantify, and changes in the timing of the return of salmon to freshwater have also affected the figures. Despite such problems, the available evidence suggests that at least on some rivers fewer adult salmon are available to be caught than formerly. Many salmon fisheries managers believe that killing sawbill ducks elevates catches, and the stomachs of some of the birds they have shot have been examined. Samples from 13 rivers show that both duck species eat juvenile salmon, though much more so at some places than at others (Figure 21). At least in the rivers of southern Scotland, the proportion of salmon in the diet is so small that it seems unlikely that killing ducks could do anything to elevate salmon catches.

Most sawbills are killed on rivers in spring in an effort to reduce their abundance during April and May, primarily to prevent predation on salmon smolts which migrate to the sea at this time of year. It is argued that the loss of smolts represents a direct loss of adult fish to a fishery because adult returns from the sea are roughly proportional to the magnitude of smolt emigration. However, our studies of duck diet show that they consume mainly smaller salmon (parr), and that the few smolts which are consumed are smaller than average (Figure 22).

On two rivers where we have counted ducks accurately, their abundance varied with river habitat, between seasons and years (Marquiss & Duncan 1993, 1994). Estimates of the food intake of ducks are beset by methodological problems and confidence intervals are wide (M J Feltham, in prep). Nevertheless, we can estimate the numbers of juvenile salmon of a variety of sizes consumed by ducks. Unfortunately, ducks take most fish from the wider and deeper sections of the river where fish populations are most difficult to estimate. Moreover, as yet there are no unbiased estimates of the proportion of parr of various sizes that return as adults to be available for harvest. Consequently, although there is a large amount of information about both ducks and fish, there still remains a great deal of uncertainty about quantitative predictions of the effects of ducks on subsequent fish catches. Some small-

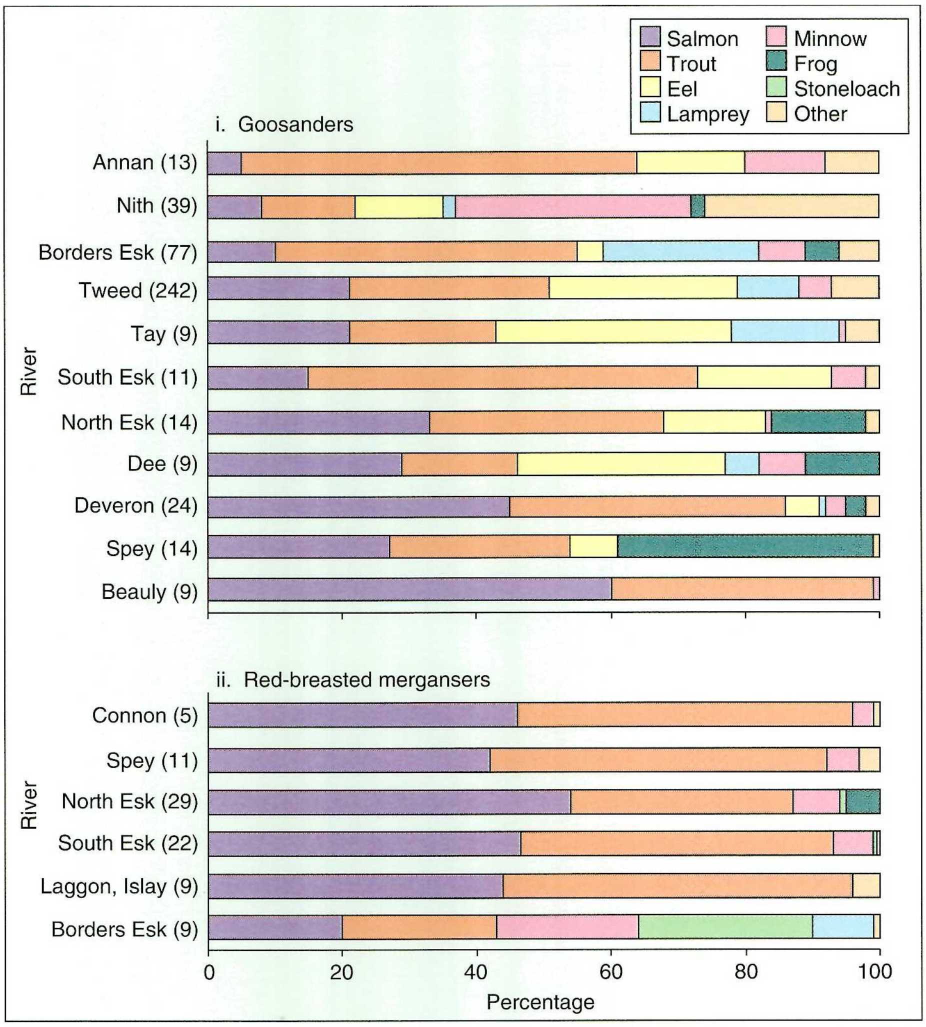

Figure 21. The stomach contents of sawbill ducks shot on various rivers in spring
i. goosanders, ii. red-breasted mergansers

scale experiments on juvenile salmon population dynamics will be informative, but they cannot address the main hypothesis directly.

Currently it is argued by some that ducks eat so many juvenile salmon that there must be an impact on the fishery, and by others

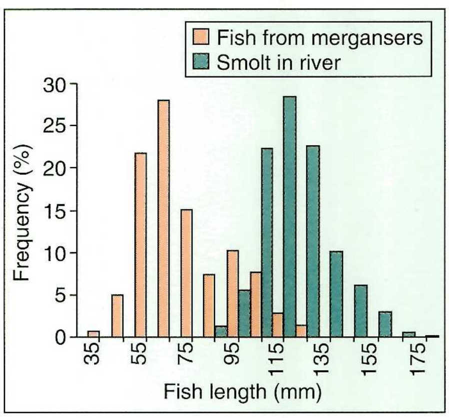

Figure 22. The sizes of 283 salmon eaten by mergansers on the river North Esk, compared with the sizes of 5000 migrating smolts

that the case against ducks is unproven. A scientific way forward would involve the experimental removal of ducks whilst measuring catches (or at least the numbers of returning adult salmon). Such field experiments are expensive but would be cost-effective no matter what the result. If ducks are causing losses of the magnitude that is claimed, experiments would provide evidence and be cheap by comparison. Conversely, if a duck effect cannot be detected, killing ducks can no longer be considered a cost-effective fisheries management technique. With no detectable duck effect, damage to salmon fisheries could not be described as 'serious', and the expensive licensed killing of sawbill ducks would become unnecessary.

M Marquiss and D N Carss

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