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The Delphi process – an expert-based approach to ecological modelling in data-poor environments

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Abstract

Resource managers are involved in difficult decisions that affect rare species and habitats but often lack relevant ecological knowledge and experience. Ecological models are increasingly being looked to as a means of assisting the decision-making process, but very often the data are missing or are unsuited to empirical modelling. This paper describes the development and application of the Delphi approach to develop a decision support tool for wildlife conservation and management. The Delphi process is an expert-based approach to decision support that can be used as a means for predicting outcomes in situations where 'absolute' or 'objective' models are unavailable or compromised by lack of appropriate data. The method aims to develop consensus between experts over several rounds of deliberation on the assumption that combining the expertise of several individuals will provide more reliable results than consulting one or two individuals. In this paper the approach is used to engineer soft knowledge on the conservation requirements of capercaillie *Tetrao urogallus*, an endangered woodland grouse, into a model that can be used by forests managers to improve the quality of forest habitat for capercaillie over extensive commercial forest areas. This paper concludes with a discussion of the potential advantages and disadvantages of Delphi and other soft knowledge approaches to ecological modelling and conservation management.

Introduction

Resource management involves complex decision making to meet a range of objectives connected to profit maximization, risk management and the provision of social outputs such as recreation, and increasingly, nature conservation. However, adaptation of management operations to meet conservation objectives is often sub-optimal because the manager lacks the necessary ecological knowledge of the species habitat requirements.

Although empirical models have been developed to assist decision making, there are a vast array of situations where existing knowledge has not been formalized in this way because the supporting scientific data are missing or inadequate. Furthermore, many scientifically competent ecological models are not fully exploited by managers because they are not 'user friendly', fail to address relevant management issues, or are in conflict with the knowledge and experience of the resource manager. In these situations, local expert knowledge and rules of thumb are often relied on.

The aim of this paper is to assess the potential for developing and applying ecological models that are derived from expert knowledge and local experience in situations where 'absolute' or 'objective' answers are compromised by lack of appropriate data, or existing models do not need user requirements. This paper focuses on the Delphi process, an expert-based approach for engineering soft knowledge. As a case study the approach is used to build a model to predict habitat quality for capercaillie *Tetrao urogallus*, an endangered species of grouse. Formally distributed throughout the boreal forests of Europe and Asia the capercaillie has been in decline primarily due to fragmentation and reduction of old growth forest (Storch, 2001). In the context of this paper the capercaillie provides an interesting case study because an objective scientific model for describing capercaillie habitat quality already exists, and can be used to independently validate the Delphi-based expert model.

The remainder of this paper is structured as follows. In the next section, the Delphi process is described with reference to previous wildlife conservation applications. The application of the process to create a habitat suitability model for capercaillie and its validation with an existing empirical model is described in the third section. A general discussion of the relative strengths and weaknesses of the Delphi approach and the use of expert knowledge in conservation management more generally is presented.

Knowledge engineering and the Dephi process

Expert knowledge is increasingly being used in ecological modelling, particularly in Bayesian statistics where expert knowledge is given the same status as any other type of data (Crome, Thomas & Moore, 1996; Martin *et al*., 2005). The Delphi process tries to add value to this knowledge by achieving consensus between experts over several rounds of investigation, on the assumption that combining the expertise of several individuals will provide more accurate results than consulting a single individual (Delbecq, Van de Ven & Gustafson, 1975). In short, the method allows the best use of currently available formal and informal knowledge in a transparent and robust way.

Originally developed during the early part of the Cold War as a means for predicting the outcome of actions in situations where absolute answers were unavailable or compromised by lack of appropriate data for calculating a solution, the Delphi process has found application in ecological modelling (Crance, 1987; Kangas *et al*., 1998). In some applications ecological variables can be weighted in terms of their overall relative importance, and scored in order to transform the physical value of the attribute (from available data) into an index representing their ecological value. In this type of application each expert independently and anonymously defines their own indices, using the same criteria, and these are then aggregated to provide a set of preliminary results representing the combined knowledge of the experts involved (Schuster *et al*., 1985).

Alternatively, the Delphi process can be used in Bayesian approaches such as Bayesian Belief Networks to identify input or predictor variables that help predict the likelihood of certain management effects (Marcot *et al*., 2001). A key core element of the Deplhi process is a consensus-building stage that involves the dissemination of preliminary results and communication between the experts to bring about convergence towards an overall solution. A group of *c*. 10 individuals is considered appropriate for a Delphi expert panel (Crance, 1987).

There are several examples of the application of the Delphi process in resource management. The Delphi process has been used in order to carry out a cost-effective analysis of woodland ecosystem restoration in Scotland with 14 experts being asked to select and weight attributes for assessing the ecological value of new native woodlands (Macmillan, Harley & Morrison, 1998). A Finnish study used the Delphi technique to help assess black grouse *Tetrao tetrix* habitat and provides an example of how expert knowledge can be used to derive a habitat suitability index from data that are already used in forest planning (Kangas *et al*., 1993, 1998). Numerical information relating to the tree species, age class distribution, stand area and other habitat variables and maps showing the distribution of different stand types for each scenario was provided to the experts. These scenarios were assessed in a pairwise manner by the experts in relation to black grouse requirements and the results analysed to provide a preliminary index of habitat suitability (Kangas *et al*., 1998). The end product was a set of planning simulations providing possible alternative forest types resulting from different management scenarios at the end of a projected 20-year period (Pukkala & Kangas, 1993).

In the USA, Schuster *et al*. (1985) used 11 experts to investigate the quality of summer habitat for elk in Montana. A networking process was used to select the experts, who were either managers of elk habitat or elk ecologists. These experts were asked to classify 171 annotated diagrams of forest structure as high-, medium- or low-quality habitat in terms of cover and forage. Summary data collected from the experts were condensed by the research team and returned to the experts to allow them to adjust their original classification in light of the general results. These re-adjusted rankings were then used as the source data for the habitat quality assessments for elk forage and cover.

More recently a Delphi approach was adapted and used to establish a Habitat Suitability Index for rare burrowing owls *Athene cunicularia* in Manitoba (Uhmann, Kenkel & Baydack, 2001). Five experts were asked to select the habitat components most important in describing habitat suitability for the owls. These were ranked and weighted using a secret ballot during a workshop. Results were then collated and sent back to the experts for comments, following which refinements were made. The final simplified and validated model was able to predict historical habitat use and brood rearing success from four variables: burrows per hectare, forage vegetation height, vegetation height at nest and inter-nest distance. Marcot *et al*. (2001) used a mixture of empirical and expert judgement derived from a Deplhi process to develop Bayesian belief networks to evaluate fish and wildlife population viability under land management alternatives.

Application to capercaillie conservation in Scotland

The capercaillie *T. urogallus* is the largest of all the grouse species. The Scottish population of capercaillie originally became extinct in 1785, but Scandinavian birds were successfully reintroduced in several phases from 1837 onwards (Pennie, 1950). Capercaillie numbers in Scotland peaked before World War One and again in the early 1970s; however, since then there has been a drastic decline in the Scottish population (Moss & Picozzi, 1994; Catt *et al*., 1998). In the mid-1970s there were *c*. 20 000 individuals (Department of Environment, 1995), but the most recent national survey, undertaken in 1998/1999, estimates that only 1073 (95% CI 549–2041) individuals exist (Wilkinson *et al*., 1999). The species is protected under Schedules 1, 2, 3 and 9 of the Wildlife and Countryside Act 1981, and Annex 1 of the European Birds Directive (Department of Environment, 1995).

Recent research of capercaillie habitat requirements typically conclude that ground flora, stand structure and forest size are the main determinants of habitat quality (Picozzi, Catt & Moss, 1992; Storch, 1993, 1995; Schroth, 1995), which suggests that the primary reason for their decline is the fragmentation and reduction of old growth native pinewoods (Moss *et al*., 2000). Although capercaillie can survive in commercial timber plantations, modern forest management practices such as no thinning regimes and premature clear felling are harming prospects of recovery. The current UK Species Action Plan for capercaillie aims to restore the species to its 1970s range by the year 2010, and a central component of this strategy is the restoration and improvement of habitat through large-scale management modifications of non-native commercial forests to create the appropriate stand structure and ground flora composition (Scottish Executive, 2001).

In this case study the Delphi process is used to develop a geographical information system (GIS)-based habitat suitability index that will support forest management decisions regarding the trade-off between conservation requirements of capercaillie and commercial timber harvesting considerations. Habitat suitability indices were first developed and used in the early 1980s. The United States Fish and Wildlife Service developed *c*. 100 species-specific models between 1980 and 1987 in order to assess the effects of different land management practices on wildlife habitat (Roloff & Kernohan, 1999; Uhmann *et al*., 2001). By assimilating information describing a target species or group of species' habitat requirements, a habitat suitability index may predict the effect of a change in habitat quality over time, or alternative habitat management, on the population in question (Uhmann *et al*., 2001; Storch, 2002).

The approach described here for capercaillie is novel in three senses. First, conventional forest inventory data on stand characteristics instead of primary ecological data are used to predict habitat suitability (this was necessary because the habitat suitability index is intended to be an integral part of a forest manager's desktop tool kit). Second, formal scientific models linking capercaillie population density and distribution to forest inventory data are not available, hence the Delphi process is used to engineer existing ecological knowledge. Third, as the model depends on forest inventory data, it is possible to 'grow' the habitat as the crop itself matures, allowing habitat succession to be explicitly incorporated into the model.

The Delphi process is typically applied over several rounds of consultation. Three such rounds were implemented in this study and an overview of the Delphi process is presented in Fig. 1. The aim of round 1 was to allocate forest compartments (The basic management unit for commercial forests is the 'sub-compartment' and each sub-compartment is described in the forest inventory in terms of a range of stand attributes. Typically a sub-compartment represents a patch of potential habitat ranging between 1 and 50 ha in area and consists of a stand of single or mixed species trees that have been planted at the same time and subjected to the same silvicultural management.) into a coherent and exhaustive classification of habitat types using information on stand structure and composition held in a conventional forest inventory database. In a large forest there are hundreds, perhaps thousands of sub-compartments and for each one the model has to be able to assign a habitat type. Based on existing literature and an initial consultation with a subgroup of experts, forest inventory data such as area, tree species, tree height and thinning regime were used to create a comprehensive typology. This consisted of 32 types described by annotated images and is similar in approach to that used by Schuster *et al*. (1985) who used 171 pictorial site representations of elk habitat derived from combinations of habitat types, ground cover types and stand structure descriptors (tree size classes and stem density classes). Five experts were initially contacted in round 1 to provide input regarding this model framework, the criteria for assessing habitat type and potential scoring systems for habitat type. Following their response each expert was met individually in order to discuss any issues raised. The revised model was then described in an 'Expert Pack' that was sent to a wider group of experts in round 2. Figure 2 describes all the habitat types that were developed and two examples are given in Fig. 3.

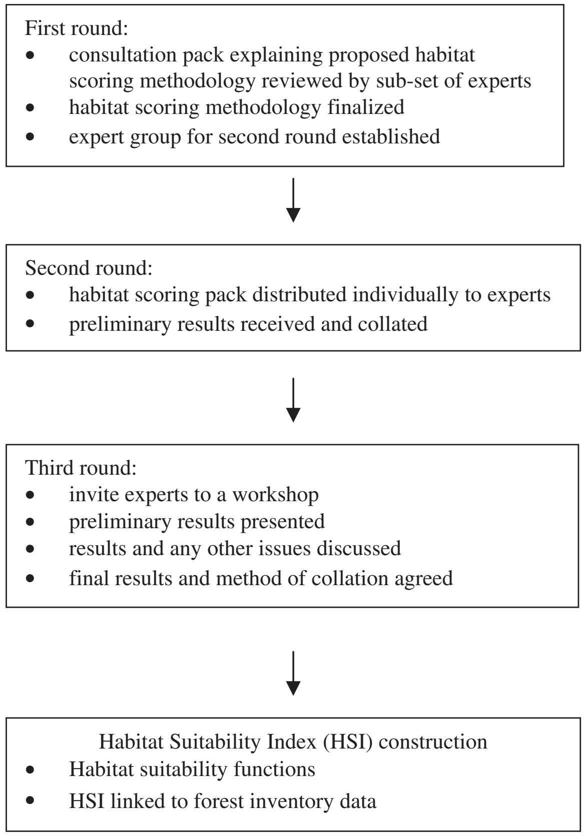

Figure 1 Summary of the Delphi process used in this study.

The 15 experts invited to participate in round 2 activities represented a broad range of research and practical expertise including both Scottish and European ecologists and foresters. Fourteen of the 15 experts contacted agreed to participate in the study. Habitat scoring packs, consisting of the background information and instructions necessary for the individual experts to implement round 2, were sent to each. The main task was to develop an area-sensitive habitat score for each habitat type: this involved scoring each habitat type between −10 (extremely unsuitable) and 10 (extremely suitable) across a range of areas (1–50 ha) representing the habitat patch sizes that are generally encountered in plantation forests. For example, if it is

Species group	Sand structure	Understory	Establishment	Restock	Pre-thicket	Thicket	Pole	Mature	Overmature
Pine	Unthinned	Grass	1	3	5			14	20
		Heather	2	4	6				
		None				7	9		
		Heather and blaeberry						15	21
	Thinned	Grass					10	16	22
		Heather							
		None							
		Heather and blaeberry					11	17	23
Spruce	Unthinned	Grass	1	3	5				
		None				8	12	18	
	Thinned	Grass						19	
		None					13		
Other habitat types									
24 Semi-natural Scots pine	25 Natural regeneration	26 Bog-pine	27 Scrub regeneration	28 Bog	29 Scots pine during transformation	30 Scots pine during transformation	31 Scots pine shelterwood	32 Windthrow	

Figure 2 All habitat types showing progression through stand development class and ground flora for all species and thinning regimes.

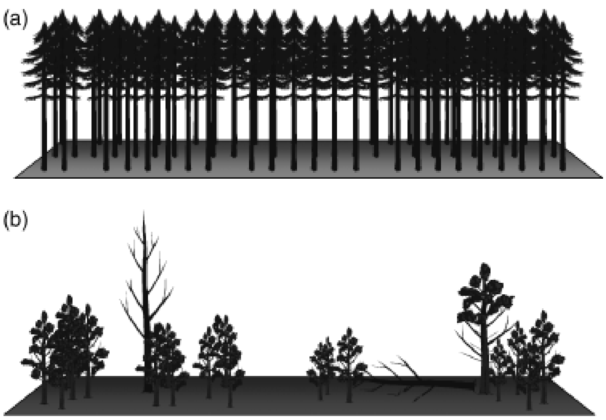

Figure 3 (a) Habitat type 12 (spruce, pole stage). (b) Habitat type 25 (Scots pine regeneration).

thought that a single large area of semi-natural pinewood would be more suitable than the two smaller areas, then a per hectare score, which increased as the area of the stand increased, would be most appropriate. The experts were told to assume that capercaillie are able to move freely within the forest and are therefore able to utilize all of the habitat types present (although this is not the reality for hens with flightless broods). These assumptions had been discussed and agreed upon during the first round of the Delphi process.

Responses varied both in terms of the range of scores and, to a lesser extent, the nature of the relationship between habitat type and area. Figure 4a and b shows two examples of scoring given by the experts. For habitat type 12 (Fig. 4a) there is a general consensus that a small area of this habitat type (dense, pole stage spruce) is of greater value to capercaillie, per unit area, than a large area. Individuals vary in how this relationship is expressed, both in terms of the rate of change in score over the area range, and the maximum and minimum scores. For example, two individuals, experts 9 and 10, believed that habitat suitability was independent of area, representing the relationship as a horizontal line. The per hectare scores for semi-natural pinewood (Fig. 4b) reflect the accepted view that this habitat type approaches the optimal for capercaillie. Because of its inherently diverse structure it may often satisfy most of the capercaillies' habitat requirements throughout the year: i.e. all of the habitat components important to capercaillie are present. For this reason, this habitat type generally receives a high score for even a small patch size, and this generally increases with area.

Following a preliminary analysis of the responses, all of the experts were invited to participate in round 3, which involved a workshop and field visit to agree on a final scoring system for each habitat type and to discuss the modelling assumptions and methodology more widely. Round 3 prompted valuable debate relating to the definition and scoring of habitat types and how to improve the link between Forest inventory data and habitat types. The main outcome was the emergence of a consensus regarding scoring for most habitat types and some re-classifications (e.g. 'failed crops' in the inventory were classified as habitat type 26: bogpine).

The individual expert scores having effectively undergone a peer review in a robust and transparent way were then used to devise habitat suitability scoring functions for a range of habitat areas (a = 1, 5, 10, 20, 30, 40 and 50 ha) that could be used in a GIS to calculate the capercaillie habitat suitability score for each sub-compartment in a forest inventory. A single habitat suitability scoring function was generated for each habitat type to summarize all individual expert scores using the following statistical

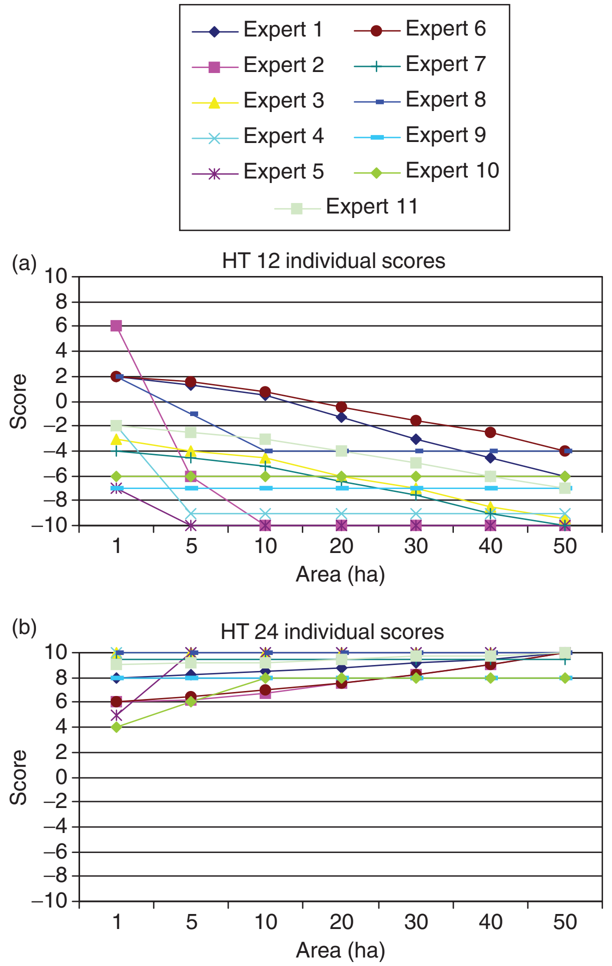

Figure 4 (a) Expert scores for habitat type (HT) 12 (unthinned, pole stage spruce). (b) Expert scores for HT 24 (semi-natural pinewood).

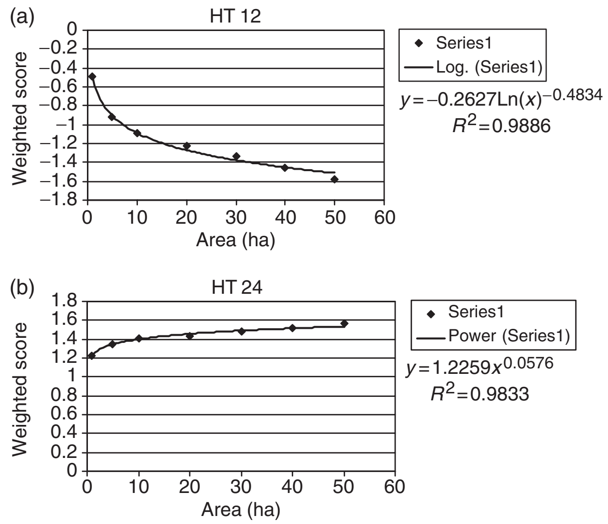

Figure 5 (a) Habitat suitability scoring function for habitat type (HT) 12 (unthinned, pole stage spruce) derived by regression from the weighted means of the scores for each expert. (b) Habitat suitability scoring function for HT 24 (semi-natural pinewood) derived by regression from the weighted means of the scores for each expert.

techniques. Prior to calculating the habitat suitability scoring functions for each habitat type the scores provided by the individual experts were standardized using the overall mean score and standard deviation. The appropriate habitat suitability scoring function for each habitat type was identified using regression fitted to the mean weighted scores for each habitat type. Lines of best fit based on the highest R^2 value were selected and these were either linear, natural log, power or quadratic in nature. In a few cases where contradictory scoring trends between experts were incorporated the R^2 values associated with the habitat suitability scoring functions were very low, typically between 0.25 and 0.5. Where the contradictions could not be explained on ecological grounds at the expert workshop, these outliers were removed from the analysis and the regression functions refitted. Figure 5a and b depicts the fitted functions for the same habitat types shown in Fig. 4a and b.

The habitat suitability scoring function was applied to the Forestry Commission inventory database for the 2353 ha forest of Glenmore: this forest was selected as a case study because it lies within a mountainous region that is one of the capercaillies' strongholds and contains a diverse range of forest habitat including a significant area of semi-natural Caledonian pinewood *Pinus sylvestris*. Figure 6 shows the distribution of predicted habitat types throughout north Glenmore based on current inventory data. Areas of semi-natural pinewood (habitat type 24) are clearly identifiable at the eastern end of the forest along with several other blocks on the southern edge. A considerable number of sub-compartments contain thinned pole stage or mature Scots pine (habitat types 10, 11 and 17) and these are distributed evenly throughout the forest. All of these habitat types contribute positively to the forest habitat score as can be seen when cross-referenced with Fig. 7 that shows habitat scores for each sub-compartment. This information can then be used by the forest manager to plan forest operations such as felling in a way that enhances capercaillie habitat: e.g. by prematurely felling younger denser crops of spruce or by converting mature stands of pine through group selection rather than clear felling. The application of the model to harvest scheduling is reported in MacMillan & Marshall (2004).

The Delphi-based expert model was validated by comparing the predicted habitat score with the earlier empirical model developed by Moss & Picozzi (1994). Their model is based on data on male capercaillie at 18 lek sites in forests ranging in structure from semi-natural pinewoods to commercial conifer plantations. Capercaillie numbers were analysed in relation to different measurements of tree and stand structure using principal component analysis (PCA). Densities of male capercaillie were found to be strongly positively associated with stands of semi-natural woodland with open structure and vigorous understory vegetation. The results of this research have been rewritten as a guide for the management of Scottish forests for capercaillie

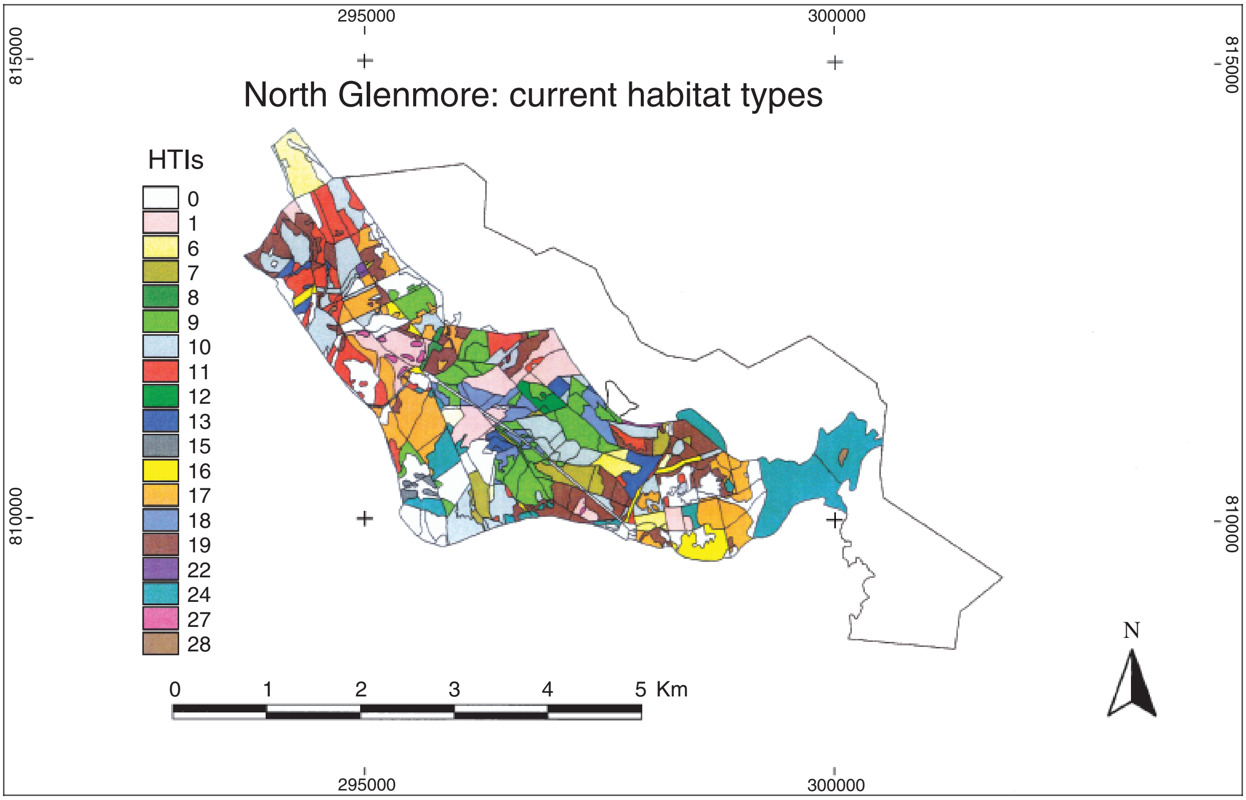

Figure 6 Distribution of habitat types as predicted by the model for the Glenmore forest.

(Moss & Picozzi, 1994) and includes a visual key for rapidly keying out and scoring capercaillie habitat on the basis of a limited number of main habitat types that reflect their structural similarity to semi-natural pine forest. The validation exercise was expected to show that the habitat types and habitat score derived from the Delphi habitat scores correspond to these four different structural types in the Moss & Picozzi (1994) key.

In the Glenmore forest, the Moss & Picozzi key was used to allocate each sub-compartment to a type with the aid of diagrammatic representations and specific measurements applied to ten trees within a circular survey plot [these being defined as having a diameter at breast height (DBH) greater than two-thirds the estimated mean DBH of all of the trees in the plot].

The degree of agreement between the two models was assessed using analyses of variance by comparing the mean predicted Delphi expert score across the four categories of Picozzi *et al*. (1992). The null hypothesis was that there is no significant difference between the mean Delphi expert scores across each of the four Moss & Picozzi categories. The results (Table 1) show that the means differ significantly between the groups ($P<0.001$) with the value of the mean Delphi score in each category positively correlated with the Moss & Picozzi score. The validation exercise conducted therefore suggests a strong positive convergence between the Delphi approach and the Moss & Picozzi model, an accepted and peer-reviewed methodology for assessing capercaillie habitat.

Discussion

The use of expert judgement is an unconventional and perhaps overlooked approach to presenting ecological knowledge in an organized and transparent way to resource managers and ecological researchers. The strengths and weaknesses of the Delphi approach relative to more empirical approaches in the context of conservation management are discussed below

An important argument against the use of expert-based values to guide decision making is the element of subjectivity such models introduce. Experts may be biased or may simply be speculating if they lack the required knowledge. Furthermore, there are several aspects of the method that can obviously affect the outcome: the selection and number of experts, the information and scoring system provided to the experts and the choice of issues discussed in order to reach a consensus (Schuster *et al*., 1985; Crance, 1987).

While an element of subjectivity is unavoidable in ‘soft-knowledge’ approaches we do not regard this criticism as a basis for rejecting the approach out of hand for several reasons. First, the Delphi approach is intended to operate in a data poor environment that precludes the development of empirical models and where the alternative is to rely on an

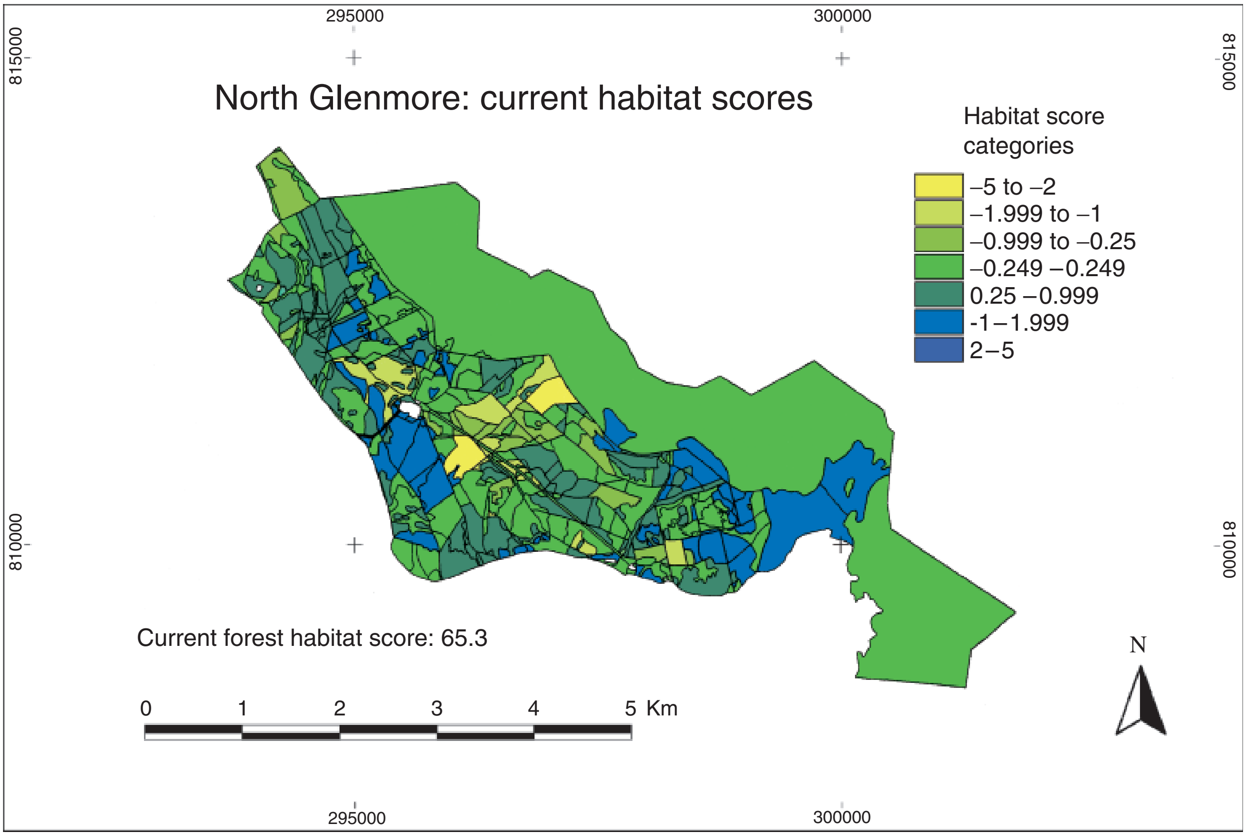

Figure 7 Habitat score for each habitat type as predicted by the model for the Glenmore forest.

Table 1 Comparison of habitat score from Moss & Picozzi (1994) and habitat suitability score using the Delphi approach

	Sum of squares	d.f.	Mean square	*F*	Significance level
Between groups	7.408	3	2.469	12.363	0.001
Within groups	9.387	47	0.200		
Total	16.795	50			

informal knowledge-based process frequently described as 'rules of thumb'. The Delphi is a more formal, transparent and consensual alternative.

Second, there is also some degree of subjectivity involved in the process of developing empirical models: e.g. in the selection of data attributes to be measured, how output is interpreted or explained, and the presence of multicollinearity effects and unspecified interactions. Third, the risk that the model will be unduly influenced by expert subjectivity is arbitrated by the nature of the process and feedback loops that are built in as safeguards. The chances of an unreliable and biased model being developed is minimized if the Delphi process is sufficiently rigorous and transparent and allows for sufficient debate and consensus building. In this example, the Delphi process involved three development stages: consultation on the proposed methodology, independent expert assessment of habitat suitability and feedback and discussion in a workshop scenario that allowed a consensus to be reached between experts. It is vitally important that the moderator of the process is experienced in consensus building and has a degree of expertise in the subject area as an effective moderator can to a large extent eliminate such effects by guiding discussions and preventing one or two individuals from dominating proceedings.

A second argument is that expert-based models are often oversimplified relative to the complexity of the ecology due to the relatively unsophisticated nature of the scoring and weighting procedure compared to highly specified and elaborate statistical analyses that are possible with empirical data sets. However, this is perhaps not so serious if one considers that models often have to be simplified if they are to be used by resource managers in day-to-day decision making. In this paper we described a model developed by Moss & Picozzi using a reasonably elaborate analysis of data to describe the relationship between habitat attributes and capercaillie density based on PCA. This model was subsequently simplified as a field guide for foresters into a series of pictorial representations describing only 12 different habitat types and four habitat scores. An important advantage of the Delphi process in this context is that the whole process of gathering data and analysis can be designed in a way that allows the eventual output to be readily applied in the form of a simple field model or, as in this case, run on a desk-top computer.

The Delphi process is highly adaptable. For example, if agreement had not been reached among the experts after three rounds, then a further refining and reapplication of the habitat scoring system could have occurred, thereby improving the quality and representativeness of the model. A further advantage for conservation-related conflicts is that the process itself is beneficial in the sense that antagonists can be 'brought to the table' to discuss controversial issues and perhaps achieve a degree of consensus: e.g. where ecological researchers can discuss differences of opinion about the science with land managers. An added advantage of this inclusiveness is that land managers may be more likely to apply the model if they have been directly involved in its design and development.

Also, intuitive reasoning by experts may be more suited to complex ecological questions than empirical modelling where the presence of confounding factors and uncertainty in model estimates can obscure the real picture. The important issues of habitat area and fragmentation in the landscape can be directly addressed in the Delphi approach, whereas these issues are difficult to investigate due to multicollinearity among relevant variables. For example, MacMillan *et al*. (1998) used the Delphi approach to assess the impact of adjacent habitat and other landscape variables on the ecological value of new native pinewoods. Storch (2002), on the other hand, using an empirical model for capercaillie habitat in the Bavarian Alps, determined that population size was difficult to predict because adequate variables representing landscape level factors such as fragmentation, other land uses and predation risk were not available.

One of the main strengths of the Delphi approach is the opportunity it provides for open dialogue between researchers and practitioners that allows the model to be conceived, developed and applied in shared intellectual space: the Delphi process is inclusive and can accommodate all stakeholders by helping to break down barriers based on perspective, prejudice or language. For example, the approach described here could be extended to incorporate at an initial stage a period of formal hypothesis building that involves the resource managers to ensure that the model is directed toward generating relevant and practical output. The process could also be extended to include further rounds devoted to model construction, to evaluate model performance and if necessary reset the initial hypothesis and objectives. A Delphi-based validation discourse would potentially help to address areas of high uncertainty that affect model predictions and help to refine model parameters using new or supplementary research in an additional round of reviews by experts.

One promising future avenue for research approach would be to develop a hybrid model using Bayesian statistics that combines soft data from the Habitat Suitability Index-expert model described here and hard empirical data used to develop the Moss & Picozzi (1994) model. Bayesian approaches, and specifically Bayesian Belief Networks, are suited to combining knowledge and experience and available scientific data. Expert knowledge is treated as an informative prior and is given the same status as any other type of data, and practical applications of integrating the Delphi approach in Bayesian statistics are emerging in the literature (e.g. Marcot *et al*., 2001). The main advantage of Bayesian analysis is that it can use mixed data (categorical, cardinal and continuous data) in the same model and can be easily updated with new data and from expert review.

In conclusion, we argue that expert-based approaches to model building deserve more attention from the academic community. Although based on subjective assessments, they can be used to capture knowledge which otherwise is ignored or undervalued simply because it cannot be measured empirically. Furthermore, we suggest that expert-based models are more likely to be used in practical situations to resolve conflicts or trade-offs with commercial activities because land managers can be directly involved in the model building and validation process.

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