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Eliciting and integrating expert knowledge for wildlife habitat modelling

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Abstract

Expert knowledge regarding the distribution of sambar deer (*Cervis unicolor*) in Lake Eildon National Park (LENP), Victoria was used to build a wildlife habitat model to assist with park management. The paper presents two methods for eliciting expert knowledge. These were a quantitative geographical information system (GIS)-based approach using a customised graphical user interface, and a qualitative approach that uses semi-structured interviews. The GIS approach is valuable as it is objective, repeatable and provides a spatial context for knowledge elicitation. Experts were asked to provide estimates of sambar sightings and predicted densities with the assistance of contextual environmental data including terrain, roads, hydrology and rainfall surfaces. The quantitative knowledge elicitation process did not identify any sambar environmental niches in the Park, and the experts disagreed about the location of likely habitat. On the other hand, the qualitative assessment showed very strong expert agreement and a combination of this information and published literature was used to build a habitat map. The results of the analysis indicate that sambar deer occur throughout the entire Park. It is envisaged that the results can be used as baseline information for population modelling and natural resource management in the Park. Elicitation of knowledge is complicated by a number of factors including computer proficiency and study site familiarity. The relatively large cohort used in this study and the inherent inconsistencies that were encountered indicate that wildlife managers should interpret results carefully from habitat models that use only a relatively small cohort of experts.
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Keywords: Habitat modelling; Expert knowledge; GIS; Sambar deer

1. Introduction

Wildlife habitat managers require detailed information pertaining to the distribution and abundance of species to help understand their ecology. Such information also may be used to develop spatially-explicit wildlife habitat models. These models can be used to determine habitat preservation priorities, identify potential risks to the species, understand the implications of different land management practices, or identify sites for the reintroduction of an endangered species (Stoms et al., 1992). Wildlife habitat models are commonly developed with the assistance of a geographical information system (GIS). This allows

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managers to examine spatially the interactions and distributions of a species and its environment.

Habitat may be characterised by a description of the environmental features that are important in determining the distribution and abundance of a species (Burgman and Lindenmayer, 1998). Burgman and Lindenmayer (1998) add that such descriptions are often based on field experience and non-quantifiable human perceptions. One widely used method for these descriptions is habitat suitability index (HSI) modelling. HSIs are based on the habitat evaluation procedure first developed by the United States Fish and Wildlife Service in the early 1980s (USFWS, 1980). The HSI for a given species and area of land represents a conceptual model that relates each measurable variable of the environment to the suitability of a site for the species (USFWS, 1996; Burgman et al., 2001). The indices are scaled from 0 (for unsuitable habitat) to 1 (for optimum conditions). Each environmental variable is represented by a single suitability index (SI), and when combined, these constitute a HSI that expresses the suitability of particular habitat for the species.

The SIs are generally linked either by multiplicative or additive functions. When the value of land as habitat depends on the presence of all variables (i.e. they do not compensate for one another), the geometric mean of their values may represent site suitability best. If the environmental variables are compensatory (one component may substitute for another), an arithmetic mean may be more appropriate (Burgman et al., 2001). Furthermore, factors may be assigned weights reflecting the relative importance of different components of the habitat (Burgman and Lindenmayer, 1998). The construction of HSIs is essentially a process for making a descriptive synthesis of information of the biology and life history of a species. This is based on a combination of the available data together with expert opinion on the species' biology (Burgman and Lindenmayer, 1998).

Expert knowledge is an important resource that may improve the reliability of modelling (Džeroski et al., 1997; Venterink and Wassen, 1997; Hackett and Vamnclay, 1998; Horst et al., 1998; Moltgen et al., 1999). It is particularly valuable where no systematic field investigations have been conducted. However, there remains uncertainty regarding its reliability (Fraser and Hodgson, 1995; Horst et al., 1998; Maddock and Samways, 2000). Radeloff et al. (1999) comment that the incorporation of location-specific knowledge of field biologists is a key step to improving GIS wildlife models, and thus improving wildlife management. A GIS may be used to achieve this and help obtain spatially-explicit habitat information from experts (Alonso and Norman, 1998; Haslett et al., 1990). This can often be achieved in real-time, which minimises the amount of data entry that is required with a large cohort of experts. In addition, the GIS provides experts with a spatial context when providing data through the inclusion of other data layers such as digital elevation models, road networks or vegetation distributions. The GIS effectively provides a virtual environment for experts that are already very familiar with what exists in the realm of the study area. The advantages of using interactive computer-based techniques such as GIS for acquiring, archiving and analysing expert knowledge are discussed in detail in Wightmann (1995) and Zhu (1999).

Sambar deer (*Cervis unicolor*), commonly referred to as sambar, were introduced to Australia in the mid 19th century. The distribution of the species in the state of Victoria is poorly understood. Boyle (1998) suggested that at least 40,000 individuals occur in Victoria, and that the range of sambar is still expanding despite an increase in hunting pressure. The impacts of sambar on indigenous flora and fauna are largely unknown, and information pertaining to the basic biological, ecological and behavioural aspects of sambar in Australia is lacking. Furthermore, management decisions pertaining to sambar are complicated by several factors including the uncertainty about the current abundance of the species, and to the difficulty of balancing hunting objectives with the broader community needs such as plant and animal conservation. Because park managers need to develop deer management policies, there remains an urgent need to collect ecological information on this species.

This paper introduces a methodology that utilises GIS and qualitative interviews to elicit information on the distribution and abundance of sambar from a group of experts with detailed knowledge of the study site. The aim is to use this information to build an accurate wildlife habitat model to assist with the management of the species. First, the paper presents a methodology for structured elicitation of knowledge that combines both quantitative (GIS) and qualitative interview techniques. The paper then examines the agreement between experts regarding the distribution and abundance of the species. This information is synthesised and combined with other data layers in the GIS to develop the habitat model. The research was conducted under conditions that are common to many management scenarios where there is little documented information on the biology of the species or its habitat.

2. Study site and species management

Lake Eildon National Park (LENP) is situated in the northern foothills of Victoria's Central Highlands, 90 km northeast of Melbourne (Fig. 1). The Park has a total area of 27,750 ha, consisting of open country, woodland and rugged forested ridges (Parks Victoria, 1997) with an extensive creek system running through the Park. The Park supports a range of rare and endangered fauna, and is managed primarily for ecosystem conservation and appropriate recreation (Parks Victoria, 1997). LENP is valued for its natural, cultural, tourism and recreational potential. An important recreational activity central to this research is deer hunting by stalking which is permitted in a specified area of the Park at particular times of the year. Developing a habitat model for sambar will help address the management requirements for LENP particularly in balancing the needs of recreational game hunters and community needs.

The total study area was defined to include the entire LENP, an alpine resort, proposed reserves (currently state forests) and freehold water authority land all adjacent to the Park. The study site was extended to include a 2-km-buffer as it would permit the inclusion of expert knowledge from areas outside the Park, but where the experts had experience. This combined study site area is denoted as LENP-2 (Fig. 1).

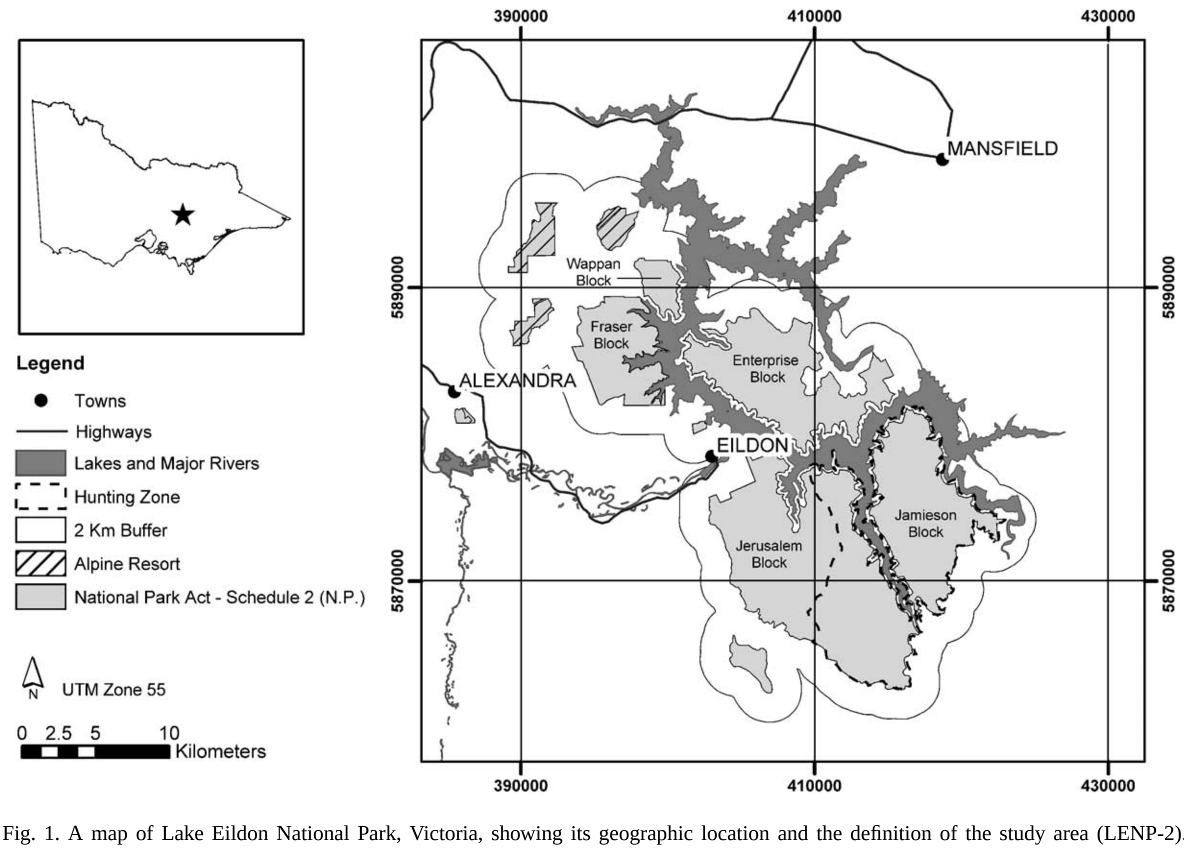

Fig. 1. A map of Lake Eildon National Park, Victoria, showing its geographic location and the definition of the study area (LENP-2).

Sambar is the third largest species of deer, and it is the largest and probably most successful of the six deer species introduced to Australia (Bentley, 1998; Harrison, 1998; NRE, 2001). A sambar stag (adult male) stands about 127 cm (50 in.) at the shoulder and weighs over 272 kg (600 lb), with females (hinds) being slightly smaller (Bentley, 1998). Sambar mainly inhabit forested areas and appear to be well suited to the Australian environment, having colonised a large part of northeast Victoria over the last century (Downes, 1983; Harrison, 1998). Due to a lack of available information on the species, this research has developed methodologies for gathering data from experts on the current distribution of sambar in LENP. This information is then analysed to explore the relationships between the species and its environment, and ultimately to build a habitat map to assist park management.

3. Methods

3.1. Introduction

Our approach involved two different phases: eliciting knowledge from experts and habitat modelling based on this knowledge. The expert knowledge was obtained using both an interactive GIS and qualitative semi-structured interviews.

3.2. Spatial database development

Because spatial context is critical for building habitat models, GIS data layers for LENP were obtained or developed. Multi-scale data layers were used for the study including 1:100,000 scale hydrology (rivers, creeks and lake boundaries) and climate surfaces from the Victorian Department of Natural Resources digital map series. Data at a scale of 1:25,000, including road networks and contours, were obtained from the Parks Victoria digital library. The entire database was re-projected to a UTM (Zone 55) projection. A hydrologically correct 10-m-resolution digital elevation model (DEM) was created using ANUDEM (Hutchinson, 1996) surface interpolation software. A DEM is the primary starting point for deriving other secondary environmental variables including slope, aspect and solar radiation and is a common input to most habitat models (see Burgman and Lindenmayer, 1998).

Slope, hillshade and aspect surfaces were derived from the DEM using ArcView's Spatial Analyst module (ESRI, 1999). The hillshade surface was used primarily to provide experts with a better representation of relief rather than for analysis. As such a sun azimuth of 90° and sun altitude of 45° was chosen as this represents the morning illumination, which is the most common sambar hunting and photographing period. Aspect was transformed to a linear measure (southness and eastness; Elith, 2002).

As little is known about sambar's ecology, preliminary discussions identified general disagreement between experts regarding whether sambar utilise only flowing water bodies such as creeks, or whether they also utilise still-water such as lakes. For this reason, two layers of proximity to water bodies (a distance surface to all lakes and major rivers, and another that contained distances to all creeks in the study domain) were used. In addition to the datasets described above, qualitative interviews with sambar experts highlighted the need for three additional datasets that could help explain the distribution of the species in the Park. These were topographic position, solar radiation receipt and distance to forest edge (see colums 1 and 2 in Table 1).

3.3. Elicitatiom of expert knowledge by interactive GIS

As most experts had little if any familiarity with GIS, a customised GIS-based graphical user interface (GUI) was developed within ArcView (ESRI, 1999) using the Avenue macro language. The GUI had two main purposes. First, it simplified the amount of interaction required by experts within the GIS framework by hiding much of the more advanced functionality and adding functionality not inherent in the native GIS software. Secondly, it automated the process of capturing data, which was stored in another GIS database in real time. Two types of information were obtained from each expert. In the first task, each expert was asked to locate sites in the study area where sambar had been seen. These sightings were recorded into the feature attribute table of the GIS data layer as point data. The second task for each expert was to predict sambar densities in 3 km × 3 km quadrats through the study site using an ordinal scale of deer

Table 1
Creation of GIS data layers and corresponding variables used in the habitat suitability index model[a]

GIS layers	Methods for GIS layer construction	SI variable	SI function
Topographic position	Calculated differences between elevation of cell of interest and mean elevation of its neighbouring cells in 200 m radius on DEM (20 m cell size).	Presence of gullies	Convert GIS layer "topographic position" to a binary gully/non-gully layer by using a threshold of −20 m, below which a cell is considered to be a part of a gully. The gully suitability index (SI_{GUL}) quantifies gullies as suitable ($SI_{GUL} = 1$) and non-gullies as non-suitable ($SI_{GUL} = 0$).
Annual solar radiation	With special purpose scripts (NSW NPWS, 1998), calculated expected solar input to a target cell on DEM for each month of the year and then for the 12-month total. Takes into account aspect, hillshade and latitudinal effects on the incoming direct and diffuse radiation (Elith, 2002).	Amount of solar radiation	Re-scaled GIS layer "annual solar radiation" to vary from 0 to 1 in order to convert it to a SI. A linear relationship between the amount of solar radiation and the SI is assumed by using this solar index ($SI_{SOL} = 1$, most suitable; $SI_{SOL} = 0$, least suitable).
Distance to forest edge	Converted an EVC[b] layer to forest or non-forest. Euclidean distance to the forest edge was estimated in ARC/INFO for each cell.	Distance to forest edge	The suitability index (SI_{EDG}) varied with distance to forest edge and with forest/non-forest. These relationships were quantified with expert opinion, as shown in Fig. 2.

[a] See Elith and Burgman (2002) and Elith (2002).
[b] Ecological vegetation classes.

density ranging from 1 (low) to 3 (high). Again, these were recorded into the feature attribute table of the GIS layer to be used for later analysis.

3.4. Elicitation of expert knowledge by interview

The GUI described above was the principal technique used to obtain quantitative data. However, qualitative information using semi-structured interview techniques was also used in the study. This process served two important aims. First, it provided a check against which quantitative estimates could be evaluated, and secondly in the event of uncertainty or ambiguity, it could assist with the habitat suitability modelling. Questions focussed on deriving the key independent environmental variables and ranking their importance for building the habitat model. The questionnaire was used primarily to guide the interview and was not shown to respondents to avoid any possible influence from the upcoming questions (B. Rohrmann, personal communication).

Nine people participated in the interviews and GIS data input, and all results were kept confidential. The participants included park managers, a local researcher, deer hunters, photographers and others who regularly visit LENP to look for sambar. The selection of these experts was based on their recreational interest in this species acquired over many years. The interviews were conducted over a 1-month period in early 2001. The knowledge elicitation required approximately 1 h for each verbal interview plus half an hour for the computer input phase via the GIS.

3.5. Data analyses

After experts concluded the GIS data input phase, the data were post-processed by deriving from each observation the environmental parameter from each of the GIS data layers that occurred at that location. Then these data were analysed statistically in order to assess the consistency between experts and to assist habitat suitability modelling. Analysis techniques are listed below.

1. The environmental domain where sambar were observed was assessed for each expert and for a

combination of all experts using box-plots. Results from the expert observations were compared against a global database created by sampling seven environmental variables (elevation, slope, aspect (eastness and southness), proximity of small creeks and of major rivers, and minimum rainfall) at 1000 randomly-located points in the GIS. These sample points were generated 20 times to compare their confidence intervals to ensure the sample was representative of the study site. If sambar occupy particular environmental niches, and if the experts have extensive knowledge of the species, the box-plots for the influential environmental variables in the study area would differ from those derived from the experts. Hunting is legally restricted to the Jamieson block and the eastern half of the Jerusalem block (Fig. 1). Therefore, all analyses were conducted for both the LENP-2 area and the hunting zone. This spatial sub-setting was used to investigate whether expert knowledge was more consistent in the hunting zone where experts had greater familiarity.

2. The ranking of predicted sambar density (low, medium and high) for each expert was examined in LENP-2 and in the hunting zone to measure the agreement amongst experts. To measure the similarity among the experts, rank correlation coefficients (Spearman's rho; Fowler et al., 1999) were derived from the ranking data. An ordination was then conducted through an eigenanalysis of the matrix of all pair-wise correlations after appropriate transformations (see Legendre and Legendre, 1998 for details of the transformation). The experts' ordination on scores were then plotted on the first two axes to illustrate associations among the experts. In this reduced space ordination diagram, approximately 74% of the variation in the full dataset and about 81% of variation in the hunting zone dataset were explained in the two axes of the ordination. Points close to each other on an ordination graph suggest that the corresponding experts are in close agreement.
3. Qualitative questionnaires were summarised to fill any gaps that might occur in the quantitative data and to obtain any information for building the HSI model.
4. The assessment of expert knowledge and the species–environment relationships then were used to build the predictive habitat model and a habitat map using the GIS. The data layers described in Table 1, Fig. 2 were then used to construct the habitat suitability map.

4. Results

4.1. Species–environment relationships

There was substantial variation in the number of observations provided by each expert, ranging from 13 to 323. This variation may be a function of differential familiarity with the study site or with GIS technology.

For the variables examined, the box-plots did not identify any particular environmental niche for sambar within the Park. Representative results are shown in Fig. 3. For several variables, including elevation and distance to lakes and major rivers, there were some inconsistencies between experts. However, these differences may be due to natural variation and possible biases in sample points that were entered by the experts. For instance, Experts 3 and 8 had the lowest number of input points (16 and 13, respectively) and produced the narrowest quartiles in much of the analysis. However, comparing the combined group of all nine experts and the global environment, the distribution of the observations of all experts was similar to the environment that represents the entire LENP.

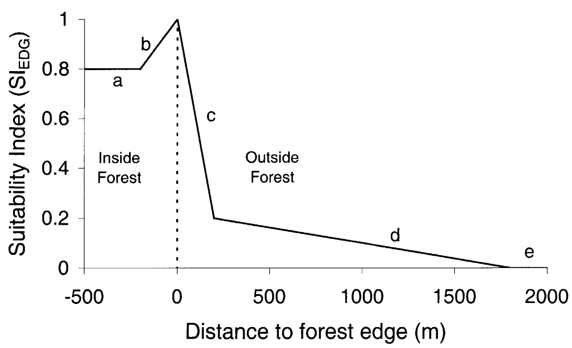

Fig. 2. The function used to convert distance to forest edge to the suitability index (SI_{EDG}). The different sections of the function are given by (a) $y = 0.8$, (b) $y = 1 + 0.001x$, (c) $y = 1 - 0.004x$, (d) $y = 0.225 - 0.000125x$ and (e) $y = 0$. Negative values for distance to forest edge represent areas within the forest.

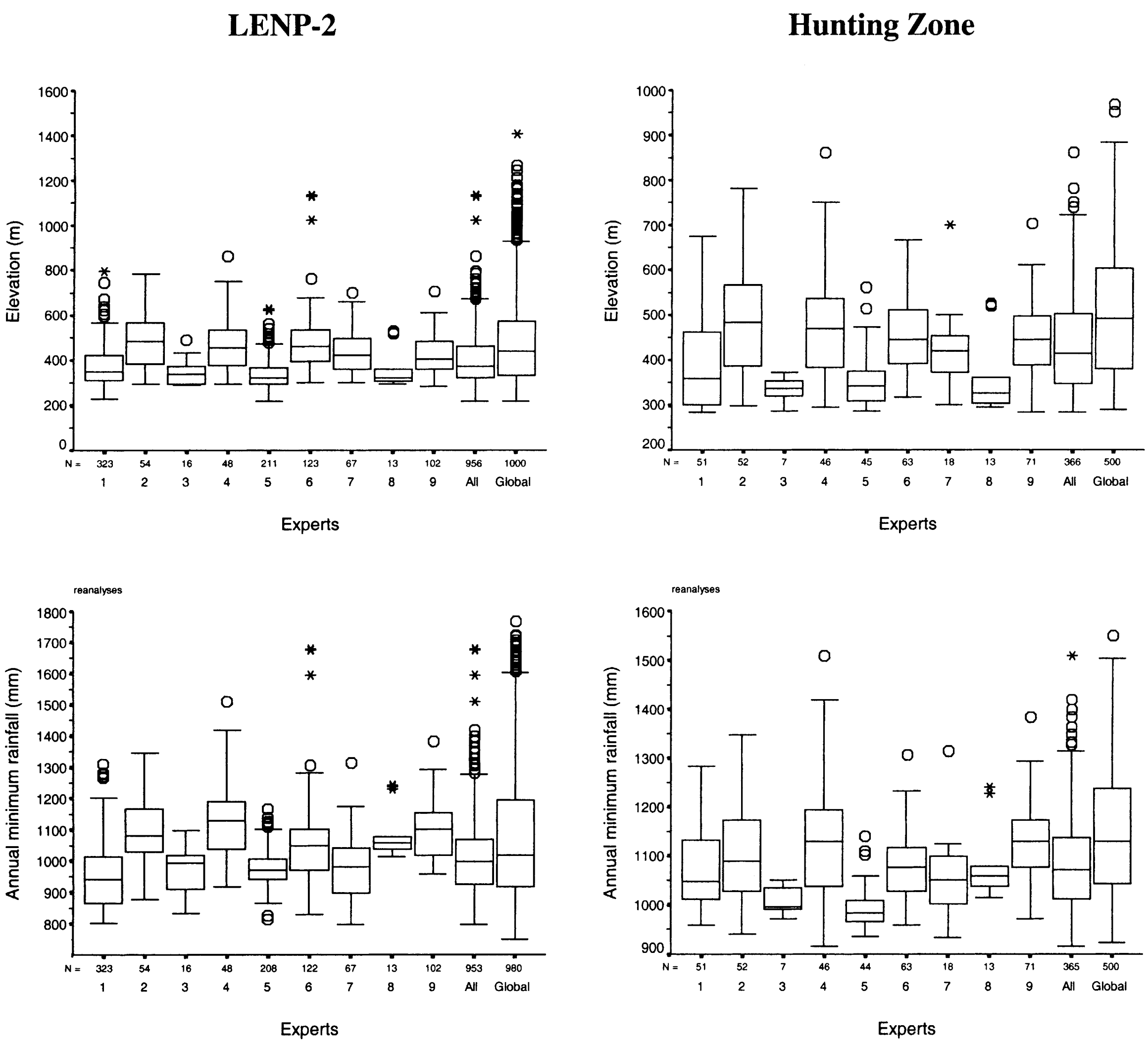

Fig. 3. Box-plots for elevation and annual minimum rainfall at sambar sites identified by experts for the LENP-2 area (left) and the hunting zone (right). Each box shows the quartiles, median and extreme values (*: extremes; o: outliers) for each expert. "All" refers to the combined group of nine experts, and "Global" refers to the global environment based on the sample points. 'N' refers to the number of cases included in each box.

4.2. Comparison of predictive sambar densities

The average predicted sambar deer density among all experts was approximately 2 (medium density) in both the entire LENP area and the hunting zone (Table 2). This matched the qualitative answers of experts that sambar occur throughout the entire Park, but are not particularly abundant. All experts except Expert 1 gave a slightly higher average ranking in the hunting zone compared to the entire LENP. The same pattern occurred in the subsequent analyses—i.e. Expert 1 provided different results from the other experts.

4.3. Ordination analyses for inter-expert comparisons

The inter-expert pair-wise comparison using Spearman's rho revealed that approximately 70% of

Table 2
Proportion for each predictive density ranking (low, medium and high) and averaged density estimates for each expert in (a) LENP-2 and (b) hunting zone

Expert no.	Proportion of ranks in each category					Mean rank[a]
	Ranking			No input	Total	
	1 (low)	2 (medium)	3 (high)			
(a) LENP-2						
1	0.37	0.16	0.34	0.13	1.00	1.98
2	0.06	0.04	0.03	0.86	1.00	1.77
3	0.16	0.28	0.30	0.26	1.00	2.19
4	0.72	0.18	0.10	0.00	1.00	1.38
5	0.05	0.13	0.09	0.73	1.00	2.12
6	0.12	0.34	0.48	0.05	1.00	2.39
7	0.65	0.28	0.08	0.00	1.00	1.43
8	0.57	0.15	0.28	0.00	1.00	1.71
9	0.46	0.44	0.06	0.03	1.00	1.59
Average	0.35	0.22	0.20	0.23	1.00	1.84
(b) Hunting zone						
1	0.72	0.17	0.11	0.00	1.00	1.39
2	0.22	0.22	0.17	0.39	1.00	1.91
3	0.11	0.11	0.67	0.11	1.00	2.63
4	0.50	0.33	0.17	0.00	1.00	1.67
5	0.00	0.39	0.06	0.56	1.00	2.13
6	0.00	0.22	0.78	0.00	1.00	2.78
7	0.11	0.78	0.11	0.00	1.00	2.00
8	0.28	0.28	0.44	0.00	1.00	2.17
9	0.00	1.00	0.00	0.00	1.00	2.00
Average	0.22	0.39	0.28	0.12	1.00	2.07

[a] Mean rank calculated on all cells with input data over (a) LENP-2 and (b) hunting zone.

Table 3
Environmental variables used in the habitat suitability index map

Environmental variables	Ecological importance	References
Presence of gullies	Sufficient water Vegetation for food Vegetation for cover/shelter Breeding sites	For all four factors: Downes (1983), Kelton et al. c.(1987), Lewis et al. (1990), Moore (1994), Bovill (2000)
Amount of solar radiation	Thermal requirement	Moore (1994), Bovill (2000)
Distance to forest edge	Grazing/foraging for wider variety of plants for food cf. forest interior	Schaller (1967), Downes (1983), Ngampongsai (1987), Lewis et al. (1990), Moore (1994), Boroski et al. (1996), Bovill (2000), Mason (2001)
	Cover	Boroski et al. (1996)
	Breeding requirement	Boroski et al. (1996), Mason (2001)
Forest	Cover: hiding, thermal and wind shelter	Downes (1983), Ngampongsai (1987), Kelton et al. c.(1987), Moore (1994), Harikumar et al. (1999)
	Food	Downes (1983), Lewis et al. (1990), Moore (1994)
Non-forest	Grass/pasture for grazing	Riney (1982), Downes (1983), Lewis et al. (1990), Harikumar et al. (1999)
	Malignant catarrhal fever (sheep associated disease)	Fyffe (2000), Animal Health Australia (2001), R. Manning, personal communication

the values of rho in the analyses of the two study domains are weakly or very weakly correlated using the interpretation of Fowler et al. (1999). The values ranged from −0.662 to 0.613 in LENP-2, and −0.710 to 0.596 in the hunting zone, and were centred close to 0. Due to large variation in the number of inputs per individual (4–40 for LENP-2 and 3–13 for the hunting zone), *P*-values are potentially misleading and thus have not been relied on in this analysis. The strongest correlations in both matrices were negative correlations among the predictions of Experts 1 and 2. The predictions of Expert 1 are ordered differently to at least half the other experts, suggesting that this expert, in particular, has a different opinion of the likely abundance of sambar through the study area. The ordination graphs (Fig. 4a and b) further differentiate Expert 1 from the other experts. There was no strong or consistent clumping in the ordination graph, and, therefore, no evidence that any of the sambar experts agree strongly with each other. However, Expert 1 tends to be isolated from the others, which suggests that his knowledge tends to oppose the common view of other experts, and especially that of Expert 2.

4.4. Analyses of qualitative knowledge

In contrast to the quantitative questions, answers from the qualitative component showed a reasonable amount of agreement among experts. It appeared that experts were able to provide relatively consistent information pertaining to sambar habitat. Three variables were consistently judged by the majority of experts to be the most critical factors that influence the presence of sambar in LENP. They were the presence of gullies, the amount of solar radiation and distance to the forest edge (see column 3 in Table 1). The ecological importance of these variables is described in Table 3. After all the interviews with the experts and examination of their responses, GIS data layers for each of these variables were used to build the HSI model and to create the HSI map (Burgman et al., 2001), where 'suitability' represents the frequency of habitat use by sambar in LENP. This qualitative information, when combined with other published evidence (refer to Table 3), was deemed sufficient to construct a HSI model. The quantitative data were not used for building the HSI model because of the high level

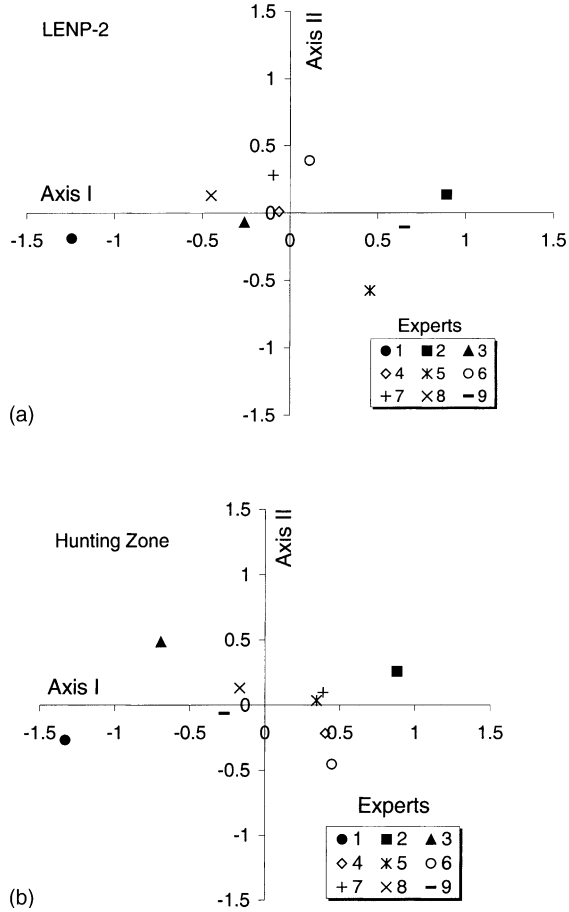

Fig. 4. (a) An ordination graph of predicted rankings of sambar density in (a) LENP-2 and (b) the hunting zone by the different experts.

of apparent disagreement among experts, including those with a similar amount experience of sambsar at LENP.

5. The habitat suitability model

Sambar is a species that can utilise habitats where some environmental conditions are sub-optional (Moore, 1994). Therefore, the arithmetic mean of suitability indices of the three variables is appropriate for development of the final HSI. Column 4 in Table 1 shows the SI functions, which transform each environmental variable to an index ranging from 0 to 1. The importance of gullies was emphasised by all the

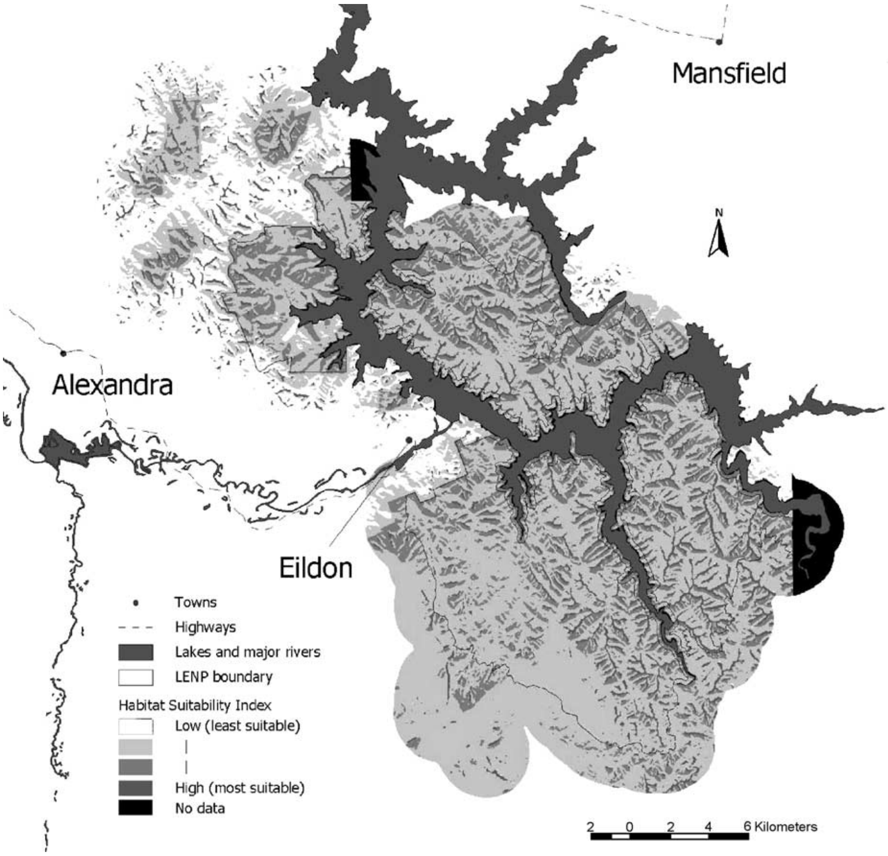

Fig. 5. Habitat suitability map for sambar deer in Lake Eildon National Park. The four classes (from low to high) represent the following ranges for values of HSI: 0.03–0.24, 0.24–0.41, 0.41–0.74 and 0.74–1.0.

experts in addition to the supporting literature, so a weight was assigned to this index (SI_{GUL}) that was twice that for solar radiation (SI_{SOL}) and proximity to forest edge (SI_{EDG}). The final HSI equation is expressed as

$$HSI = \frac{2 \times SI_{GUL} + SI_{SOL} + SI_{EDG}}{4} \quad (1)$$

Eq. (1) was implemented in the GIS using map algebra and the respective input layers to produce the HSI map. This final map classifies the LENP area according to different degrees of suitability as sambar habitat (Fig. 5). The darker regions on the HSI map indicate where frequencies of habitation by sambar are expected to be highest. The modelled niche of sambar does not occupy large and contiguous geographic patches in the Park, but it rather shows large areas of forest that are at least partially suitable for sambar, with many small-scattered patches of higher suitability. These small patches highlight gullies and sites of higher potential solar radiation.

6. Discussion

6.1. Knowledge elicitation from experts-observations from GIS interaction

The sambar experts participated in the knowledge elicitation process with a great deal of interest and enthusiasm. This interest and enthusiasm was particularly evident when they provided responses to the qualitative questions. Some limitations hindered the information elicitation process in the quantitative phase of the study. Experts were commonly unfamiliar with computers or GIS software, and hence there was some reluctance when inputting deer observations. For instance, a number of experts elected not to zoom into areas to refine their choices and chose to input their data at a scale of 1:400,000, which generalised much of the spatial detail available in the GIS databases. Even when we sat beside them and encouraged them to use a more detailed scale and ensured that they knew how to do so, they chose to work at the larger extent. In these instances, they chose a scale that would not lose sight of the Park boundary and would continue to provide them with good spatial context at a relatively coarse scale. This is interesting when one considers that their knowledge of the Park is obtained at ground level; this behaviour may reflect use of maps for navigation.

The provision of a variety of key GIS data layers was expected to help to provide the experts with a geographical context during the knowledge input stage (Haslett et al., 1990; Crossland, 1992; Alonso and Norman, 1998). However, experts commonly ignored much of this contextual data and resisted viewing various combinations of data layers. This again may have adversely affected the knowledge elicitation process. At the same time, this suggests that a layer in the database representing the maps or aerial photos that the experts use in the field would be very useful to improve the precision and reliability with which sambar sites are located.

Correlation is likely to exist in some of the data obtained by experts. For example, some of the environmental attributes identified at the locations provided by the experts are correlated (e.g. rainfall and elevation). Further, when inputting the data, the experts tended to work across the GIS, meaning that some sites would be entered as clustered. This may reflect the areas of LENP that they best, but would probably give rise to autocorrelation in the data. Such autocorrelation is likely to give somewhat spuriously tight ranges in the perceived habitat of sambar, so the ranges presented in Fig. 3 may be underestimated.

Because of inconsistency and uncertainty in the quantitative information provided by the experts, the qualitative data became more important than initially envisaged. Nevertheless, GIS and modelling techniques can be important sources of knowledge for wildlife biologists (Radeloff, 1996) and are particularly important at the prediction stage. Without further research addressing these cognitive issues associated with acquisition of knowledge, it is difficult to determine how objective and reliable the GIS-based GUI approach is in eliciting expert knowledge. Previous researchers have developed methodologies for eliciting knowledge from experts (e.g. Džeroski et al., 1997; Venterink and Wassen, 1997; Hackett and Vamnclay, 1998) ranging from mailed questionnaires through to methods based on artificial intelligence. Despite the range of methods that are used, all tend to encounter difficulties, especially with regard to internal consistency (e.g. Džeroski et al., 1997). Based on these previous studies, and the results of our research, checking for inconsistency in expert opinion appears to be important, and development of methods to resolve the inconsistencies is warranted.

6.2. Inter-expert knowledge consistency

As noted earlier, a greater degree of expert agreement was observed using the qualitative knowledge elicitation process, in comparison to the quantitative technique. Although the experts had varying site familiarity ranging from 7 to 138 days per year, their knowledge regarding the physical and behavioural characteristics of sambar habitat requirements remained consistent. The experts that behave as outliers in the ordination graphs (i.e. in the quantitative analyses) in Fig. 4a and b have in fact more experience and familiarity with the study site than those experts that are clustered. For example, Experts 1 and 5 visit LENP approximately 120 and 138 days per year, respectively, while Experts 6 and 8 spend only about 7 and 10 days per year. It may be that the clustered experts have similarly inadequate knowledge of the study area and the species. In contrast, the two experts with extensive site familiarity (Experts 1 and 5) occupy diametrically different positions on the ordination graph. This contradictory result from qualitative and quantitative input may be due to differences in the experts' perceptions of sambar habitat, inconsistencies between what is believed and what occurs in the field, and error in locating sambar sites during the GIS sessions. More research on the influence of subjective judgement among experts is required to identify reasons for this behaviour.

One area of agreement between the results of the qualitative judgement and the quantitative assessment is that both techniques imply that the entire region of LENP provides at least somewhat suitable habitat for sambar. Reasons for these results may include:

- Experts can discriminate suitable habitat for sambar in LENP, but technical factors regarding human–computer interactions and cognitive issues prevented them doing so;
- Only some of the experts can discriminate suitable sambar habitat in the Park as not all have complete knowledge of the species or of the study area (Fischhoff et al., 1982; Puuronen and Terziyan, 1999; Zhu, 1999);
- Sambar are still too poorly understood by any experts for sufficient data to be available for building a habitat model; and
- The suitability of habitat is similar across the entire extent of LENP.

6.3. *Relationships between sambar and its environment*

Ideal sambar habitat should provide adequate food, water, shelter and breeding sites and these conditions coexist best in gullies (Kelton et al., c.1987; Interviewees, personal communication). Hence, this factor is deemed as an excellent indicator of sambar habitat in LENP. Results from the qualitative interviews also identified forest edges and potential solar radiation as two additional variables that can help determine sambar habitat, and these variables were used to develop the final habitat map. The habitat map shows that to some extent, the entire Park constitutes suitable habitat for sambar as at least some of these habitat requirements occur somewhere in the Park. This is consistent with the findings of Lucas (2002) that suggest population numbers are stable or increasing in LENP. This may help explain why quantitative knowledge elicitation yielded few conclusive results in terms of identifying particular sambar niches. An alternative reason, which also relates to result that the sambar locations identified by the experts were not confined to any particular environment of LENP, is that expert knowledge may not be adequate for this type of analysis. In the long term, the model needs to be reviewed routinely as more information regarding the species becomes available.

6.4. *Assumptions and uncertainties*

The final habitat model reflects what the experts believe to be true with regard to the environmental conditions suitable for sambar in LENP. The result relies on the validity of two main assumptions. First, there is the inherent assumption that qualitative expert knowledge is reliable. Secondly, it relies on the assumption that the spatial data are of a sufficient accuracy and scale to both describe the site to the experts and to build the habitat model. Evaluating the results with an independent set of field observations of sambar distribution can validate the HSI model and map, and also some of the underlying assumptions (e.g. Elith and Burgman, 2002).

7. Conclusions and recommendations

This research has presented and evaluated a quantitative GIS-based and a qualitative interview-based technique for eliciting knowledge from wildlife experts. The aim was to identify suitable sambar habitat to build a habitat map to assist with the management of the species in the Park. The research also sought to answer questions of knowledge reliability as expert knowledge is being increasingly used for natural resource management. This was achieved by analysing the degree of inter-expert consistency. Results show that expert agreement varied widely. However, further validation of the methodology can only be achieved with detailed field studies and long-term monitoring of the species to understand its habitat preferences. The methodology used in this paper could be improved by consulting more experts and by improving the GIS layers to reduce error in locating sambar sites.

The GIS-based approach was important as it provides experts with spatial context in a repeatable, objective and structured framework. It also simplifies data management, analysis and construction of spatially explicit habitat maps. The statistical analysis of quantitative deer sighting data did not identify any particular sambar niches in LENP, and this was consistent with the outcomes of the qualitative assessment. In the first instance, the lack of an identifiable sambar niche may have been due to cognitive issues associated with the use of the GIS by the experts. For instance, the experts were asked to make decisions at a scale that may have been unfamiliar to them. It is also possible that their knowledge of the species was inadequate, with knowledge being insufficient to discriminate among the variation in habitat quality across the Park at the scale required. More importantly, the results indicate that natural resource managers should act with caution when relying on expert knowledge from relatively small cohorts of experts.

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