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A predictive diagnostic model for wild sheep (*Ovis orientalis*) habitat suitability in Iran

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A B S T R A C T

Wild sheep (*Ovis orientalis*) as the true ancestor of domestic sheep (*Ovis aries*) is currently listed as vulnerable (VU) by IUCN. Effective conservation of this species requires collecting all available ecological knowledge into a single framework that could be used for management decision making. Use of Bayesian Belief Networks for such purposes have been advocated over recent decades as this approach can integrate different sources of knowledge and perform comprehensive analyses. We built a decision support tool using BBN to assist in habitat management of wild sheep populations throughout the species' geographical range. The behaviour of the model was tested using scenario and sensitivity analysis. Habitat security, food and water suitability, and thermal cover were recognised as the main habitat variables determining wild sheep habitat suitability. Integrating the complex interactions between variables, the model can be applied for both diagnostic and predictive analyses answering "what if" and "how" questions. This approach can assist wildlife conservationists for building similar models for other poorly-studied threatened species.

Introduction

Successful wildlife management, including conservation and recovery plans, requires a comprehensive understanding of wildlife population and environmental variables in the face of uncertainty. Applying decision support tools to threatened species can facilitate adaptive conservation. Wild sheep or mouflon (*Ovis orientalis* Gmelin, 1774) populations have been decreasing both in size and geographical range in Iran. Poaching, habitat destruction and competition from livestock have been recognised as the main causes of population decline (Valdez 2008). As a consequence, IUCN has determined the conservation status of this species as Vulnerable (A2 cde) since 1996. Wild sheep is distributed from Turkey to Kazakhstan in the north, to Iran, Pakistan and India in the south. Iran, as the central distribution zone of the species, holds a significant part of the species abundance and genetic diversity (Valdez et al. 1978). *O. orientalis* is recognised as the true ancestor of domestic sheep (*O. aries*) (Hiendleder et al. 2002) and has the potential to cross-breed with its domestic descendant (Hosseini et al. 2009). This represents both the conservation importance of the species and the associated hybridisation risk. Due to the degradation of habitat and the presence of different threats in most parts of the species' distribution range, Asiatic mouflon rarely occurs outside the Iranian protected areas.

Conservation and management of wildlife populations in Iran have hitherto mostly relied on protection of areas where the species of interest occurs. Knowledge of ungulate ecology is incomplete and chiefly exists as personal experiences of field biologists and wildlife experts. The unavailability of reliable data and scientific knowledge at the time of decision making by wildlife managers and policy makers are among the reasons for the failure of conservation programmes. There is an urgent need to collect and combine the available information to provide a base for adaptive management of threatened species particularly when their ecology is not thoroughly studied.

Scientific knowledge is the result of research questions, testing hypothesis and publishing the results and conclusions in books, databases and journals. This sort of knowledge is usually scarce for wildlife species occurring in developing countries. To fill in data gaps, experiential knowledge of wildlife experts and local opinions could be another source of valuable information. This is often not formally documented, but still has great value for management. Traditional ecological knowledge of local experts comes from years of experience through testing of different strategies (Fernandez-Gimenez 2000). This knowledge is orally transferred through the generations and is continually adapted as socio-economic and environmental conditions are changing (Bashari 2006).

Management of wildlife species in such situations requires comprehensive analyses taking all existing relevant ecological information from different sources into account, while determining the uncertainty in the analyses. Bayesian Belief Network (BBN), which is a graphical model that incorporates probabilistic

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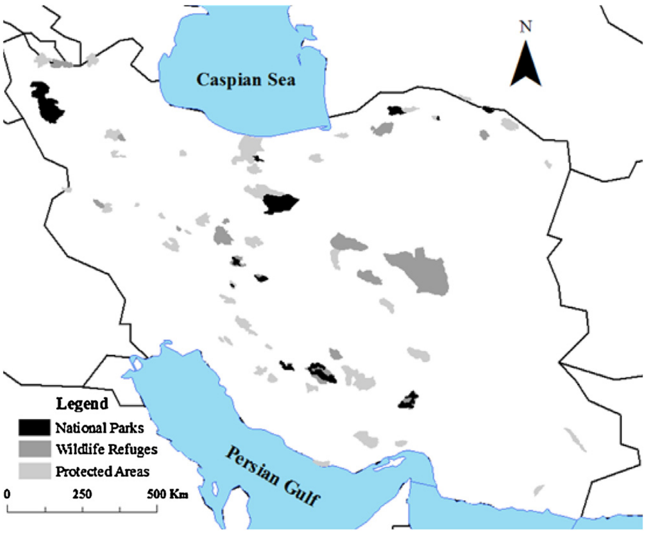

Fig. 1. Iran's protected areas containing wild sheep.

relationships among variables of interest, provides the opportunity for such analyses. BBNs also offer a visual tool for communicating the uncertainty associated with potential management outcomes to conservation practitioners and decision makers, and they can also be readily updated as new evidence becomes available. The importance of applying past experiences and expert knowledge for decision making in wildlife management have been previously acknowledged (Cain 2001; Martin et al. 2005; Smith et al. 2007). Also the practical guidelines for developing, testing and revising BBNs for wildlife and ecological assessment have been provided (Marcot et al. 2006).

Wildlife conservationists often rely on empirical knowledge as a basis for their management programmes. However, managers frequently face situations where urgent decision making is unavoidable. The empirical knowledge gained by managers can potentially be used in adaptive management approaches. Using available information on the species ecology including published literature, unpublished data and expert knowledge, we built a general predictive diagnostic BBN model as a decision-making support tool for managing wild sheep populations throughout the species geographical range. The developed model also provides information on the environmental factors influencing wild sheep habitat suitability and may be adapted for particular populations or other related ungulate species.

Methods

Species distribution and habitats

In Iran, wild sheep generally inhabit arid and semi-arid mountains, foothills and rolling steppes, and occur in contrasting climates from the cold heights of the Alborz and Zagros Mountains to the relatively hot and humid rocky shores of the Persian Gulf (Ziaie 2008) (Fig. 1). The mean annual precipitation in areas of occupancy of the species in Iran ranges approximately from 100 mm in the central desert to more than 400 mm in the northern and north-western part of the country (Darvishsefat 2006). Plant species such as *Artemisia* spp. and *Astragalus* spp. can be seen in most of the distribution range of the species (Pabot 1967). The main predators of Asiatic mouflon are grey wolf (*Canis lupus*) and leopard (*Panthera pardus*), which occurs sporadically in wild sheep habitats (Ziaie 2008).

Suitability modelling

The development of the habitat suitability model involved two main steps. First, a conceptual model (influence diagram) was developed and it was converted into a predictive BBN model. Secondly, the behaviour of the model was tested using scenario and sensitivity analysis (Fig. 2). The details of each step are explained further below.

Conceptual model development

Developing an influence diagram was the main purpose of this step. An influence diagram is a generalisation of Bayesian networks representing the system variables and the links between them, which assist in understanding the relationships between the system variables. In the influence diagram the key environmental variables believed to affect the wild sheep habitat suitability were captured. The suitable habitat for wild sheep is defined as an area, which offers food, security and thermal cover for feeding, mating and avoidance of predators.

Initially, we constructed a draft influence diagram based on a comprehensive literature review on wild sheep habitat suitability (e.g. Kermani Alghoreishi 2002; Maleki-Najafabadi 2008; Maleki-Najafabadi et al. 2010; Pahlevani 2004; Shams-Esfanabad 2010; Ziaie 2008). We followed Marcot et al. (2001) and Smith et al. (2007) for drafting the influence diagram. In the next stage, follow up workshops were conducted with three experts who had conducted long term research on a population of wild sheep (excluding the authors) to elicit their expert knowledge. The influence diagram was then modified according to the experts' opinions. According to the level of available information, an appropriate number of states were selected for each node (variable) in the influence diagram (e.g. for 'habitat security' we used "high" and "low") to ensure the desired precision and accuracy (Marcot et al. 2001). The states of the nodes allow running different possible scenarios by populating parent nodes. The influence diagram contained causal influence of the 'key environmental variables' on 'main habitat variables' and 'main habitat variables' on 'habitat suitability' (Fig. 3).

Eliciting probabilities for the model

In the next step, the revised influence diagram was converted into a BBN using Netica software (Norsys Software Corporation 2008). Each node (variable) was converted to a set of discrete states, and arrows were used to represent cause and effects relationships between the variables. Conditional Probability Tables (CPTs) were then adjusted to explain the strength of the dependencies between the variables.

The amount of available published information about wild sheep suitability models was not adequate to extract measured probabilities for all available scenarios and could only be obtained from long-term studies. To produce a predictive model, the CPTs in the influence diagram were therefore populated using the available documented information and subjective probability estimates obtained from wildlife scientists who participated in building the influence diagram.

A CPT calculator was used in the probability elicitation process to check for logical consistency of the probabilities (Cain 2001). The CPT calculator works by reducing a CPT to the minimum number of scenarios for which probabilities need to be estimated. These scenarios allow the CPT calculator to determine the relative influence of each factor on the probability of outcomes. Once probabilities for these scenarios are elicited, the calculator checks for logical consistency and interpolates probabilities for all scenarios in the CPT.

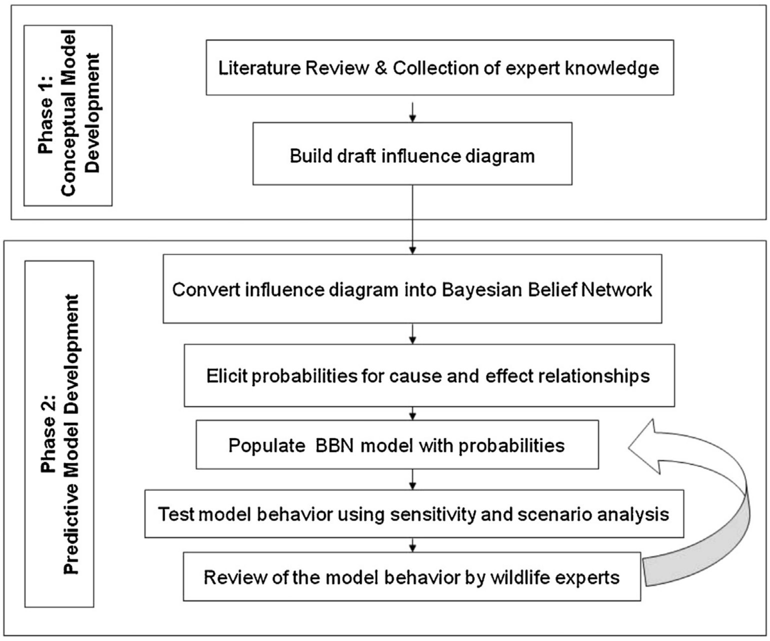

Fig. 2. Steps used to build a predictive Bayesian Belief Network model for wild sheep habitat suitability.

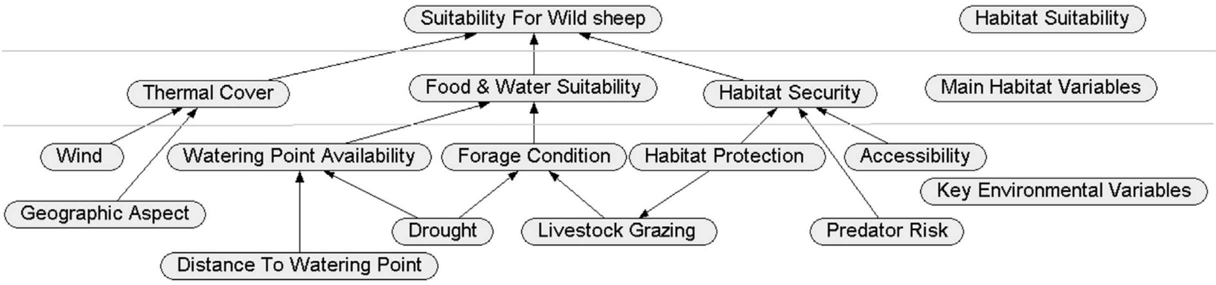

Fig. 3. Framework used to construct an influence diagram for wild sheep habitat suitability. The model shows the cause and effect relationships between 'main habitat variables' including food suitability, habitat security, thermal cover and a number of 'key environmental variables' with suitability for wild sheep.

To test the behaviour of the completed BBN model, two kinds of sensitivity analysis were performed: (1) a comprehensive sensitivity analysis incorporating all the variables used in the model; (2) sensitivity analyses separately for the main child nodes (variables directly influenced by their immediate neighbour variables). The results of either of these sensitivity analyses were then compared with the expectations of wildlife experts involved in the probability elicitation process to validate the model's behaviour. The measure of sensitivity used was entropy reduction (Marcot et al. 2006). We used an iterative process and if the results of sensitivity analysis did not meet the experts' expectations, the conditional probability tables were readjusted accordingly. This process continued until they agreed on the relative order of influence of key environmental variables on main habitat variables and main habitat variables on habitat suitability.

Results

The developed model contains key environmental variables, main habitat variables and habitat suitability nodes (Fig. 4). In the diagram, habitat security, food and water suitability, and thermal cover are considered as the main habitat variables determining wild sheep habitat suitability. The states and the definitions for each node in the influence diagram are presented in Appendix 1.

As an example for a prediction through the process of a "what if analysis" environmental and habitat variables for Ghamishlou Wildlife Refuge (32°_430′ N, 50°_520′ E) in spring 2012 is provided in Fig. 4. Being in the spring season, there is very low chance of snow (2%) as well as livestock grazing (10%), while forage condition is more likely to be favourable. Having this setting and considering the fair condition of wind in this season (60%), the thermal cover will be in good condition (88%). In spring when there is no drought and the distance to watering points is fair, watering point availability is also more likely to be in good condition. Snow effect, elevational gradient distance to mountain, and slope, all influence the predation risk. Inserting Ghamishlou key environmental variables in the model, a low predation risk is resulted (73.9%). As the refuge is protected the accessibility is moderate, and considering a low predation risk, habitat security happens to be rather high (82.4%). Good condition for watering point availability (90%) and favourite forage condition (93.5%) lead to good food and water suitability (86.1%). Under this scenario the model is predicting the most likely suitability for wild sheep as being high (80%).

The model can also be used in diagnosis mode to answer "how" questions. For instance, the model may be applied to answer 'how might the suitability of a particular habitat be poor'? This condition is most likely if habitat security is low, and forage condition is rather unfavourable. The model also shows that livestock grazing reduce food and water suitability.

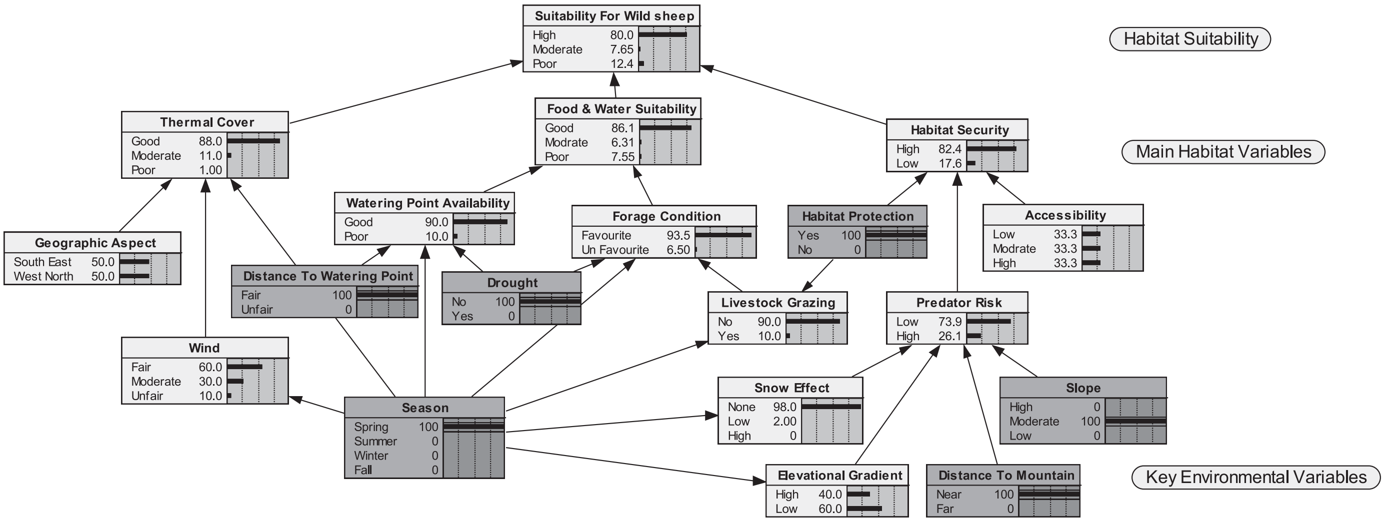

Fig. 4. Suitability for wild sheep in the form of a Bayesian Belief Network for prediction. Each node in the model has a number of states (for example high and low for habitat security), which allows analysis of different scenarios of the input (or parent) nodes to the output (or child) node (suitability for wild sheep). A scenario (season is 'spring', slope is 'moderate', habitat protection is 'yes', drought is 'no', distance to watering point is 'fair' and distance to mountain is 'near') has been inserted by selecting particular states for the nodes shaded grey. Under this scenario the model is predicting the most likely suitability for wild sheep to "high" (80%).

Table 1
Summary of sensitivity analysis performed on the habitat suitability and main habitat variables of the BBN model. The order of variables and their entropy reduction indicated the "mutual information" or their importance level. Variables with similar distance to the target variable (habitat suitability) are shown with the same shading (dark grey: main habitat variables; light grey: key environmental variables directly connected to main habitat variables; and no shading: outer key environmental variables).

Nodes	Mutual information	Variance of beliefs
Habitat security	0.536	0.108
Habitat Protection	0.180	0.041
Livestock grazing	0.128	0.029
Accessibility	0.025	0.006
Thermal cover	0.019	0.004
Food & water suitability	0.019	0.005
Forage condition	0.017	0.004
Predator risk	0.011	0.003
Season	0.007	0.002
Distance to mountain	0.003	<0.001
Wind	0.002	<0.001
Snow effect	0.002	<0.001
Watering point availability	0.002	<0.001
Drought	0.001	<0.001
Slope	<0.001	<0.001
Distance to watering point	<0.001	<0.001
Elevational gradient	<0.001	<0.001
Geographic aspect	<0.001	<0.001

Sensitivity was calculated as (Marcot et al. 2006): $I = H(Q) - H(Q|F) = \sum_q \sum_f \frac{P(q,f)\log_2[P(q,f)]}{P(q)P(f)}$, where I is the expected reduction in mutual information of Q (measured in information bits), $H(Q)$ is the entropy of Q with q states before any new findings, and $H(Q|F)$ is the entropy of Q after new finding from node F with f states.

The sensitivity analysis suggests that habitat security is the most important habitat variable influencing wild sheep habitat suitability (Table 1). The results of sensitivity analysis on child nodes are summarised in Fig. 5. This figure highlights the relative influence of input nodes on habitat variables by showing the amount of anthropy reduction caused by changing the probability of parent nodes classes. Again, habitat security (determined mainly by habitat protection) arises as the most influential factor on wild sheep habitat suitability. Thermal cover and food and water suitability as the second order important factors have the same influence on habitat suitability. Distance to mountain has more influence on predator risk than slope, snow effect and elevational gradient. When performing overall sensitivity analysis as presented in Table 1, main habitat variables receive a higher importance level on average (mean anthropy reduction = 0.191) compared to directly connected key environmental variables to main habitat variables (mean anthropy reduction = 0.031) and outer key environmental variables (mean anthropy reduction = 0.018), as the key environmental variables have less or no parent nodes inputting influential weights to them. Performing sensitivity analysis separately for each child node as presented in Fig. 5, indicates the importance level of the proximate parent nodes of a given child node without diluting the influence of outer nodes.

Discussion

According to the sensitivity analysis, habitat security (determined by habitat protection, accessibility and predation risk) is the main determinant of site appropriateness for wild sheep. Habitat protection was recognised as the most important factor determining habitat security. The importance of habitat protection is discussed further in section on management implications. Following habitat protection, accessibility of wild sheep habitats to human interference is another crucial factor determining the habitat security. The increasing trend of road and highway construction has increased the accessibility to the wild sheep habitats and decreased habitat security. Apart from increasing accessibility, roads cause more disturbances and fragment habitats. In addition, protected areas with a higher ratio of perimeter to area are more accessible to human interferences (Bennett 2003).

Predators such as grey wolf, leopard, lynx and feral dogs are reported to prey on wild sheep (Ziaie 2008). Distance to escape terrain has more influence on predator risk than slope, snow and elevation. Wild sheep occasionally move to foothills for grazing in early spring (Ziaie 2008). The risk of predation is highest in the plains for this mountainous species. Slope is also closely related to

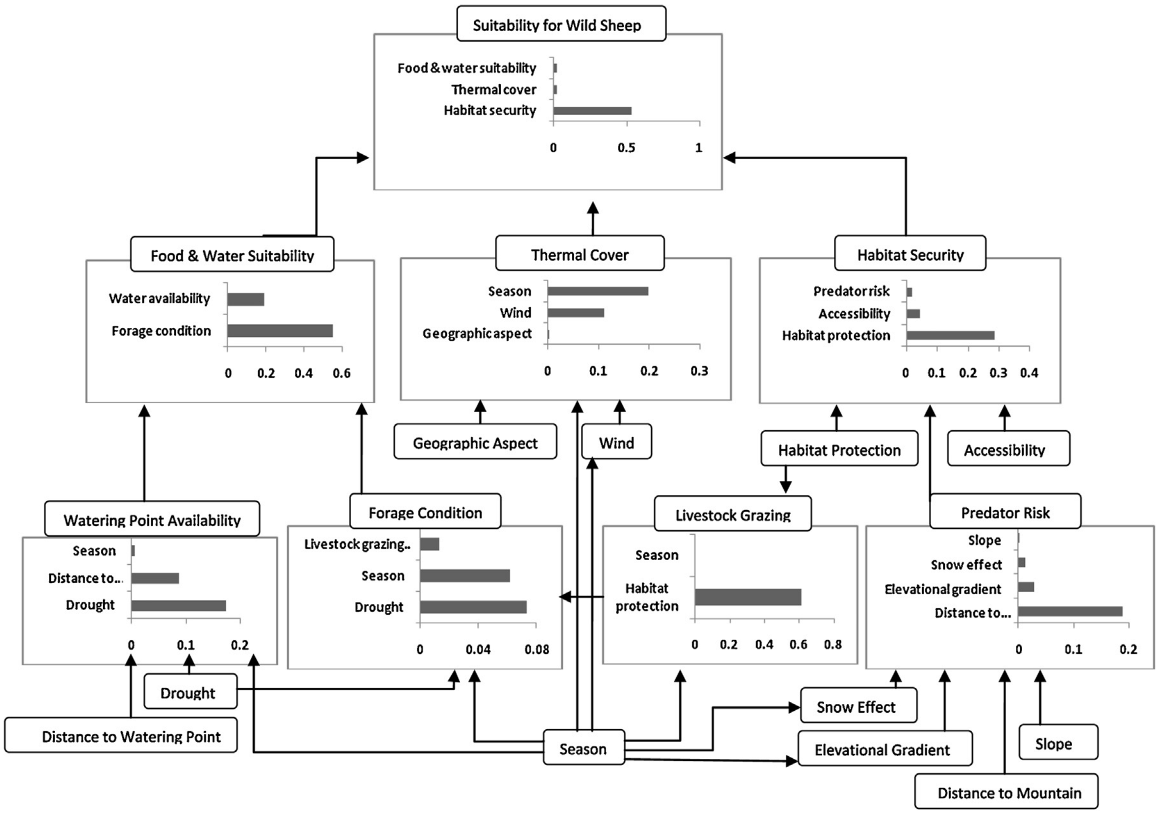

Fig. 5. Sensitivity analysis of child nodes to variations in their parent nodes. The effect of parent nodes on child nodes (consist of CPTs) are shown in the graph for each child node. The horizontal axes represent the amount of anthropy reduction based on mutual information in the sensitivity of the selected nodes due to finding at other nodes.

escape terrain, but as long as the species is within the mountains, the escape terrain is accessible. The effect of snow is seasonal. In most parts of the distribution range of the species, the snow may cover the habitat for only a couple of months.

Next to habitat security, the sensitivity analysis suggests that thermal cover and food and water suitability have the same influence on habitat suitability. Thermal cover is determined by season, wind and geographic aspects. There is a trade off between loss of energy (thermal cover) and energy intake (food availability) (Van Beest et al. 2012). As there was no evidence about the importance of one of these factors (food availability and thermal cover) over the other, they received the same weight in the model.

Factors such as forage condition, presence of snow, livestock grazing and dominant winds alter with season. Other factors including thermal cover, elevational gradient and water availability are more dependent on the species habitat requirements, which change with season. For instance, the frequency of visiting water-points increases as the weather gets warmer (Maleki-Najafabadi et al. 2010). Similarly, Shams-Esfanabad (2010) revealed that the preferred elevation and geographic aspect and generally the distribution of suitable habitats of wild sheep change by season.

Management implications

This study confirmed the importance of protected areas for conserving wild sheep populations. In Eurasia, wild sheep populations are rarely seen outside protected areas. IUCN has recognised poaching and interactions with livestock as the main threats to wild sheep throughout its geographical range (Valdez 2008). Effective protection can considerably reduce both illegal hunting and livestock grazing pressure. Protection not only enhances habitat security, but also provides more resources such as water and forage for wild herbivores in the absence of domestic animals. The extent and distribution of the protected areas containing a population of wild sheep are relatively good. However, the capability of maintaining viable populations in the long term is a matter of question. Hemami and Groves (2001) reported a considerable number of extinctions of gazelle (*Gazella* spp.) populations within the protected areas. Amongst the required factors contributing to the efficacy of the protected areas is law-making (Cirelli 2002) and law enforcement (Fischer 2008; Hilborn et al. 2006), and wildlife management, which is not seriously practiced in Iran.

Iranian Department of Environment (DoE) manages four classes of protected areas including National Parks, National Natural Monuments, Wildlife Refuges and Protected Areas. No wild sheep population occurs within any of the National Natural Monuments, which protect a physical or living feature. In addition, DoE defines areas where hunting is prohibited for a specified period of time as No Hunting Areas. These areas along with National Parks, Wildlife Refuges and Protected Areas constitute four levels of protection for wildlife in Iran. The level of protection decreases from National Parks to No Hunting Areas. Livestock can freely enter No Hunting Areas and most parts of the Protected Areas and Wildlife Refuges in grazing seasons (Kolahi et al. 2012). Hence, with the exception of National Parks, competition and other interactions with livestock remain potential problems in No Hunting Areas and to some extent in other reserves (Malekian & Hemami 2012).

The model presented in this paper illustrates the influencing factors on habitat suitability of wild sheep, which in turn can affect the expected performance of the population. We encourage conservationists of the countries within the distribution range of the species to use this model for assessing the effects of their management practices on wild sheep habitat suitability before implementing the management activities (the CPTs data are available from the authors on request). By monitoring and calculating growth rates of a number of wild sheep populations across a large part of the species distribution range, it will be possible to obtain an index of actual habitat suitability for the studied populations. The accuracy of the model could then be assessed by comparing the expected (model predictions) and the (index of) actual habitat suitability.

The model provides the opportunity for managers to consider season in their “what if analyses”. Management practices should be planned separately for each season e.g. the proper distribution of water should be considered particularly in summer. In winter, southern slopes may be preferred (Shams-Esfanabad 2010) as receive more sunshine and as a consequent have higher percent cover of annual plants. Therefore, for delineating the border of protected areas, the presence of slopes with different aspects should be quantified.

The failure of conservation strategies adopted by Iran’s Department of Environment (e.g. the strategy of relying solely on protection through establishing protected areas) highlights the need to understand factors influencing the species habitat suitability, the interaction between these factors, and the importance of adaptive management. The developed BBN model is a large scale model incorporating an array of wild sheep habitats with different environmental conditions. Such general models can potentially provide a basis for establishing adaptive management programmes. Having the assistance of wildlife modellers, it will be possible for wildlife managers to adapt the current model to build site-specific models based on the habitat characteristics of the sites under their management. They may need to remove, add or modify new nodes or node classes. It will also be possible to add a GIS layer into the BBN model to map the suitability of wild sheep habitats (Smith et al. 2007).

As Smith et al. (2007) pointed out; such a BBN approach provides a low cost and updatable tool for structuring the available knowledge for managing threatened species. This is particularly useful for wildlife conservation in developing countries where the level of knowledge is usually not enough for building data hungry models. As new knowledge may easily be included in an existing BBN, it may continuously be used for solving newly emerging management problems (Howes et al. 2010). With this modelling framework an expert comparing different possible scenarios may also achieve objective-based management decisions.

Acknowledgements

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Appendix 1. Definitions for nodes and their classes in the suitability for wild sheep BBN model.

Node	Definition and classes
Season	This node represents the season of interest. Spring: the season of interest is spring. Summer: the season of interest is summer. Winter: the season of interest is winter. Autumn: the season of interest is autumn.
Suitability for wild sheep	The most suitable habitat for wild sheep is a site which has a high security and thermal cover and there is no limitation in food and water supply. High: areas with high security and thermal cover, food and water supply. Moderate: areas with moderate security and thermal cover, food and water supply. Poor: areas with limited security and thermal cover, and lack of food and water.

Appendix 1 (*Continued*)

Node	Definition and classes
Food and water suitability	This node represents areas where quality food is available and water resources are accessible. Good: areas where quality food is available and water resources are in the vicinity. Moderate: areas where forage is available to some extent and water resources are not located in the vicinity, but are within a reasonable distance. Poor: areas where limited food or water resources are available.
Security degrees	This node represents the security degree of a site with regard to predation risk and man-induced threats. High: areas with low predation risk and man-induced threats. High slopes and areas far from main roads (particularly within the protected areas) have the highest security degree. Low: areas with high predation risk and man-induced threats. Unprotected flat areas relatively close to main roads received the lowest security degree.
Thermal cover	This node represents the availability of habitat features that help the animal to save energy. Good: areas with fair wind and geographical aspect with regard to the season. For instance in winter, low elevations facing south and east without wind provide the best thermal cover. Moderate: areas where wind and geographical aspect are not fair with regard to the season, but are tolerable. Poor: areas with unfair wind as well as geographical aspects with regard to the season. For instance in winter, high elevation windy areas in north and west aspects provide the poorest thermal cover.
Water availability	This node represents the availability of water resources to satisfy drinking requirements of wild sheep with regard to the season and energy consumption. Good: areas with unlimited access to water. Poor: areas with limited access to water.
Forage condition	This node represents the quantity and quality of forage. Favourable: sufficient high quality food is available. Unfavourable: forage is limited and or of low quality.
Livestock grazing	This node represents the relationship between grazing pressure by livestock and forage availability for wild sheep. No: there is no livestock grazing, or still sufficient forage is available for wild sheep after livestock grazing. Yes: insufficient forage available for wild sheep due to livestock grazing.
Habitat protection	This node represents the protection status of wild sheep habitat. Yes: the area is protected. No: the area is not protected.
Predator risk	This node represents the risk of predation by carnivores with regard to the habitat features. Low: the risk of predation is low because escape terrain is close. High: the risk of predation is high because escape terrain is far or absent.
Accessibility	This node represents the accessibility of the habitat with regard to the shape of the area (e.g. edge effects), distance to main roads and or human settlements. Low: edge effects are negligible and the area is far from main roads and or human settlements. Moderate: edge effects are moderate and there is some distance to the main roads and or human settlements. High: edge effects are high and main roads and or human settlements are in the vicinity of the area.
Geographic aspect	This node represents the area of the suitable aspect of terrains with regard to season. South/East: the most suitable expositions for the cold season. North/West: the most suitable expositions for the hot season.
Wind	This node represents the frequency of windy days and its severity. Fair: the wind does not limit the animal’s vital activities. Moderate: the wind limits the animal’s vital activities to some extent.

Appendix 1 (*Continued*)

Node	Definition and classes
	Unfair: the wind limits the animal's vital activities.
Watering point availability	This node represents the availability of watering points for wild sheep. Good: the distribution of watering points is suitable for wild sheep. Poor: wild sheep access to watering points is limited.
Drought	This node classes whether or not drought is present at the site of interest. Drought occurs when rainfall lies below ten percent of average precipitation. No: no drought. Yes: drought.
Slope	This node represents the frequency of the defined slope ranges. High: the higher slope ranges are dominant. Moderate: the moderate slope ranges are dominant. Low: the lower slope ranges are dominant.
Elevational gradient	This node represents if there is sufficient elevational gradient for seasonal migration. High: broad elevational gradient is available. Low: limited elevational gradient is available.
Snow effect	This node represents the effect of snow for wild sheep with regard to predator risk. None: there is no snow. Low: snow cover does limit wild sheep escape ability to some extent. High: snow cover significantly limits wild sheep escape ability.

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