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# Modelling cheetah relocation success in southern Africa using an Iterative Bayesian Network Development Cycle

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ABSTRACT

Relocation is one of the strategies used by conservationists to deal with problem cheetahs in southern Africa. The success of a relocation event and the factors that influence it within the broader context of long-term viability of wild cheetah metapopulations was the focus of a Bayesian Network (BN) modelling workshop in South Africa. Using a new heuristics, Iterative Bayesian Network Development Cycle (IBNDC), described in this paper, several networks were formulated to distinguish between the unique relocation experiences and conditions in Botswana and South Africa. There were many common underlying factors, despite the disparate relocation strategies and sites in the two countries. The benefit of relocation BNs goes beyond the identification and quantification of the factors influencing the success of relocations and population viability. They equip conservationists with a powerful communication tool in their negotiations with land and livestock owners, which is key to the long-term survival of cheetahs in southern Africa. Importantly, the IBNDC provides the ecological modeller with a methodological process that combines several BN design frameworks to facilitate the development of a BN in a multi-expert and multi-field domain.



## 1. Introduction

The current status of the cheetah (*Acinonyx jubatus*) is Vulnerable, V*U C2a*(*i*). This status means that it is considered to have a high risk of extinction in the wild, that the estimated population size is fewer than 10,000 mature cheetahs and that there is a continuing decline in the numbers of mature cheetahs. There is also no subpopulation with an estimated size of more than 1000 mature cheetahs (IUCN, 2007). At the turn of the 20th century cheetahs still inhabited vast areas of Africa and Asia and were found in at least 44 countries, stretching from the Cape of Good Hope to the Mediterranean, the Arabian Peninsula and the Middle East, India and Pakistan in southern Asia and the southern provinces of Russia (GCCAP, 2002; Marker, 2002). Since then the cheetah population worldwide has declined from approximately 100,000 cheetahs in Africa and Asia to around 250 cheetahs (*Acinonyx jubatus venaticus*) in Iran (IUCN, 2007) and in sub-Saharan Africa the number of cheetahs (*Acinonyx jubatus jubatus*) is estimated at between 12,000 and 15,000 (Marker et al., 2003). Sub-Saharan Africa contains the only remaining viable free-ranging cheetah populations (Marker et al., 2003) with Kenya and Tanzania in East Africa, and Namibia and Botswana in southern Africa, being the two main cheetah strongholds in Africa (GCCAP, 2002). The main reasons for this negative trend in cheetah numbers are interspecific competition, increased contact and conflict with humans and fragmented habitat (GCCAP, 2002).

Cheetah conservation organisations in southern Africa face the daunting task of addressing these issues to ensure the long-term viability of free-ranging cheetah populations. In South Africa and Botswana relocation is one of several methods used to conserve cheetahs (Purchase et al., 2007). This involves trapping cheetahs that are perceived by landowners to be problem animals and releasing them into other areas. The successful relocation of a cheetah, or group of cheetahs, was the focus of a Bayesian Network (BN) modelling workshop held in South Africa which was attended by cheetah experts from South Africa and Botswana. The objective of the BN model was to increase the survival of the greater cheetah metapopulation, informed by the success of a relocation event.

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Bayesian networks are popular for modelling complex and multi-faceted environmental issues (Castelletti and Soncini-Sessa, 2007; Marcot et al., 2006; Smith et al., 2007) such as predator relocations. A BN is a mathematical model (Pearl, 1988; Neapolitan, 1990; Jensen and Nielsen, 2007) that consists of a graphical depiction of random variables and a probabilistic framework that describes the strength of the relationships between the variables (Jensen and Nielsen, 2007). BNs are a useful statistical tool for collating, organising and formalising information such as empirical data, model outputs, secondary sources and expert knowledge about the issue of concern (Uusitalo, 2007). They have been used in very diverse applications, such as forensic science (Taroni et al., 2006), toxic algal bloom initiation (Hamilton et al., 2007), environmental impact of fire-fighting methods (de Waal and Ritchey, 2007) and urban land use classification from satellite imagery (Park and Stenstrom, 2008). The graphical form that BNs take are that of a directed acyclic graph, comprising a set of random variables (factors) represented as nodes and linked through directed arrows to one or more variables depicting the outcome(s) of interest (target node(s)) (Jensen and Nielsen, 2007). The network is quantified through a series of conditional probabilities based on the available information (Borsuk et al., 2006; Taroni et al., 2006; Jensen and Nielsen, 2007).

Various types of BNs (traditional, object oriented, dynamic) may be used to model a variety of ecological problems. Traditional BNs are suited to many situations, but inadequate when modelling large complex domains (Uusitalo, 2007). These are better served by Object Oriented Bayesian networks (OOBN). OOBNs provide a framework for modelling large complex data structures by simplifying the knowledge representation and facilitating reuse of nodes and network fragments (Koller and Pfeffer, 1997). Another specialisation of the BN is a dynamic Bayesian network which is essentially a traditional BN with a temporal dimension (Weber and Jouffe, 2006) where interdependent entities change over time (Ross and Zuviria, 2007). Dynamic BNs are used to model time series data (Ghahramani, 2001) and are ideally suited to object oriented modelling techniques (Jensen and Nielsen, 2007).

This paper describes the development of a BN for the evaluation of a successful relocation of wild cheetahs using the new IBNDC heuristic. Success is here defined in terms of short-term survival of the relocated cheetah(s) and long-term population viability of the cheetah population in light of the relocation. The paper synthesises the experience of South Africa and Botswana as representative countries for cheetah relocation. These two countries were selected for three main reasons. First is the range of relocation experiences: although both have experience in relocations, South Africa has had substantial experience whereas relocation is still relatively new in Botswana. Second are their geographical locations: they are neighbouring countries with predators known to move freely between the countries (Marnewick et al., 2007), therefore conservation management practices in one country are bound to impact on the other. In particular cheetah home ranges are known to span both countries. Third is the variety in relocation sites: the two countries have quite different types of areas available for relocation and their practices in relocating cheetahs also differ.

The paper proposes an original heuristic method; an iterative BN development cycle (IBNDC) to create a decision-support system that consolidates available information and experience of experts from different countries. The IBNDC approach organises opinion to better understand the inter-relation of factors that affect relocation of cheetahs and metapopulation viability, and helps to guide the choice of sites for a successful relocation.

## 2. Methods

### 2.1. Study area

South Africa and Botswana had different options with relocation sites, but the key factors identified as critical to ensure successful relocation were endorsed by all. Relocation sites in South Africa

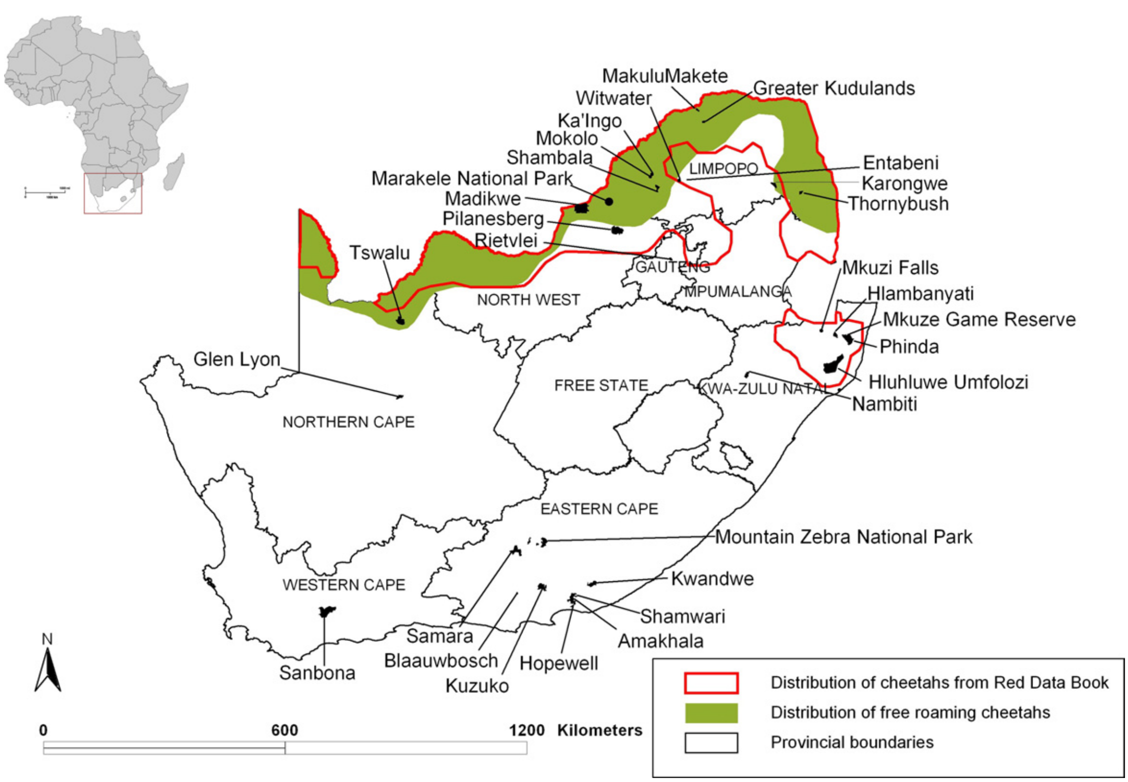


**Fig. 1.** Current cheetah distribution and relocation sites in South Africa (Marnewick et al., 2007).

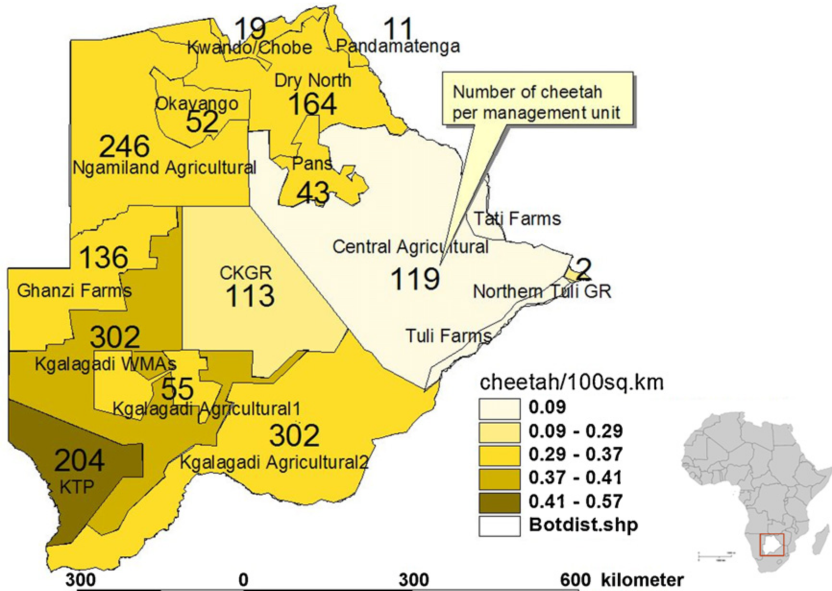


**Fig. 2.** Cheetah estimates in Botswana by predator management zones (Klein, 2007).

(Fig. 1) are scattered widely throughout the country, with several located at the northern border with Botswana where the South African free roaming cheetah population occurs (Marnewick et al., 2007). The majority of South Africa (approx 70%) is privately owned with state-owned, protected areas totalling less than 5% (Cummings, 1991). This has necessitated the creation of a metapopulation management plan to manage geographically separated populations of endangered predators such as cheetahs and wild dogs *Lycaon pictus* (Lindsey et al., 2005) as a whole.

Cheetahs are distributed sparsely throughout Botswana (Fig. 2) with roughly two thirds of the land area providing suitable habitat (Myers, 1975). This includes areas in the arid zone and the lush Okavango Delta in the north-west of the country (Myers, 1975). Although Botswana has large areas that could support cheetah populations, there are concerns about the degradation of this habitat, because desertification, overgrazing and lack of fresh water resources are serious environmental issues that face Botswana (BCP, 2002).

Four different types of relocation sites were identified. These comprised *Protected and fenced*, *Protected and unfenced*, *Unprotected and unfenced*, and *In situ*. In situ relocation occurs when the land owners where the cheetahs were trapped agree to have the animals released back into their home range. This may happen after consultation between land owners and conservationists. In South Africa relocations are mainly done into fenced protected areas and occasionally in situ relocations are done. The options in Botswana are relocations into unfenced protected areas or unprotected areas and in situ relocation.

### 2.2. Iterative Bayesian Network Development Cycle (IBNDC)

The Bayesian networks were conceptualised and quantified during a 4-day workshop, bringing together cheetah experts from South Africa and Botswana and statisticians from South Africa and Australia. As described in Section 1, a Bayesian network typically comprises one or more target nodes and a set of factors linked directly or indirectly with these node(s). For cheetah relocation, the design requirements were: multiple linked target nodes (success of a particular relocation event and a viable free-ranging cheetah population), multiple networks for a given target node (success of a relocation event to relocation sites with different characteristics) and growing expert knowledge and experience. In addition, it was agreed to be prudent to cater for possible expansion or transformation of these networks into dynamic and object oriented BNs and to satisfy adaptive management requirements so that the cheetah relocation BNs learn from subsequent relocation events. Consequently the uncertainty present at the time of modelling diminishes in light of new evidence and experience (Bosch et al., 2003; Smith et al., 2007). A modelling approach, the Iterative BN Development Cycle (IBNDC), was developed to suit these varied objectives and was used at the workshop. It consists of two primary processes: a *Core process* and an *Iterative process*.

The *Core process* is performed once when modelling commences, typically in a workshop setup, and is vital to the subsequent iterative phases embodied in the *Iterative process*. The *Core process* is a largely manual process, demanding interaction between experts and comprising the definition of target nodes, identification of key factors and grouping of subnetworks. In contrast, the *Iterative process* consisting of four iterative phases, can exploit many automated features of the BN modelling software application, in addition to the input from experts. The iterations explicitly focus on the definition, quantification, validation and evaluation of subnetworks prior to consideration of the whole model. For the purpose of modelling cheetah relocations, this was very useful for three reasons: a seemingly large task was broken down into more manageable components; there was early and continuous feedback to the participants; and the subnetwork summary (or target) nodes were of interest in themselves. The four iterative phases were continually revisited as the network structure and its quantification were crystallised.

Figs. 3–5 describe the IBNDC heuristics. Fig. 3 is a visual representation of the key IBNDC concepts and illustrates the identification and definition of the outcome(s) of interest (target node(s)) as pivotal to all the subsequent steps (Varis and Kuikka, 1999). For example, key factors (nodes) are identified and described in relation to the outcome(s) of interest and consequently belated changes to the target node(s) may negate key factors described prior to the change. A unified modelling language (UML) Use Case diagram (Fig. 4) depicts the interactions between the expert teams and the IBNDC processes. Fig. 5 shows a UML Activity diagram with a detailed account of the steps involved in following the proposed IBNDC methodology.

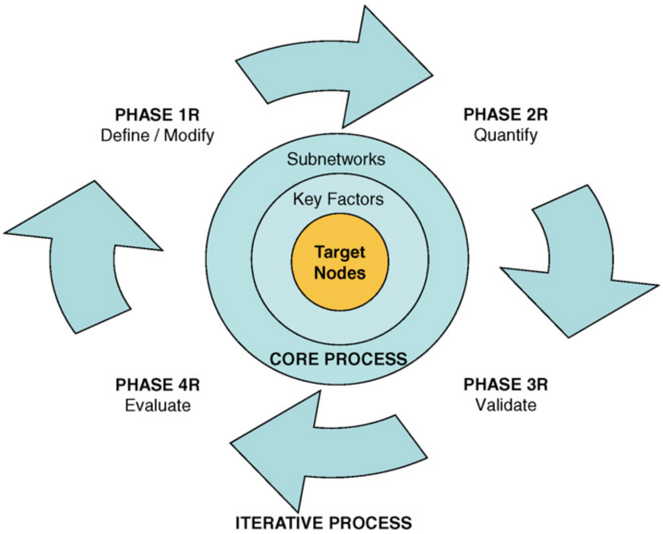


**Fig. 3.** Conceptual representation of the Iterative BN Development Cycle (IBNDC).

### 2.2.1. Core process

The three steps of the *Core process* are shown in the IBNDC Conceptual diagram in Fig. 3. Step 1 occurs at the centre of the IBNDC, and is arguably the most important step of the process as this encapsulates the objective of the model: *What issue do we want the model to address*? (Varis and Kuikka, 1999). This is the end-point or final aim of the network and is represented in the BN as the target node. Careful definition of the target node is crucial to the structure, assumptions and identification of the key factors of the ensuing network. During the workshop much discussion focused on the definition of two target nodes – a successful relocation event (*Success - site*), and a viable wild cheetah population – (*Success - long term*) expressed in such a way that they could be represented probabilistically. As represented by its insularity from the rest of the development cycle in Fig. 3, the target nodes were not changed once agreement had been reached by all stakeholders, as such changes would have negated the rest of the network. Step 2 required not only the listing of relevant factors, but also their definition. Sticky notes were used to brainstorm these factors for the two target nodes. For Step 3, the sticky notes which logically belonged together were arranged into several smaller coherent groups, which would form the basis for subnetworks in the overall network. At this point the information was transferred into the Hugin® BN modelling software and the different groups of nodes were colour-coded for clarity. This marked the start of the *Iterative process*.

### 2.2.2. Iterative process

The Iterative Process was applied to each of the groups defined in the Core process and then to the overall network. Iterations continued for a subnetwork (or overall network) until there were no more changes received from Phases 1R and 4R (Fig. 5). The first iteration of Phase 1R (Define/Modify) for the overall.

BN entailed reviewing the nodes that were defined in the *Core process* and then creating a conceptual model of the network, including the placement of nodes and the connection of nodes through directed links. Ensuring accurate documentation of the node definitions is important in the interpretation of the interactions with other nodes. The node definitions were documented in Hugin® and then used to generate network documentation of the cheetah relocation BNs. Node definitions were frequently referred to during the development of the BN to ensure consistent interpretation of the factors by all experts. The second and subsequent iterations added, deleted or modified nodes and directed links, as dictated by the results from Phases 3R and 4R (Fig. 5). These iterations were performed for each of the subnetworks before considering the overall network.

In Phase 2R (Quantify) the states of the nodes were defined and the underlying conditional probability tables (CPT) populated. It is advisable to limit the number of states of a node and parent nodes to prevent unwieldy probability tables (Marcot et al., 2006). Nevertheless it can be quite a daunting task for experts to complete the CPTs (Pollino et al., 2007b), especially when there are subtle variations in the combination of states of the parent factors or when the combination of factors presents a theoretical than a realistic scenario. In these situations it was constructive to encourage the experts to prioritise the relative importance of the parent nodes. This enabled the remaining CPT values to be populated based on the more plausible combinations which the experts felt comfortable and confident about specifying. The remaining probabilities were calculated by using the relative weights (importance) of the

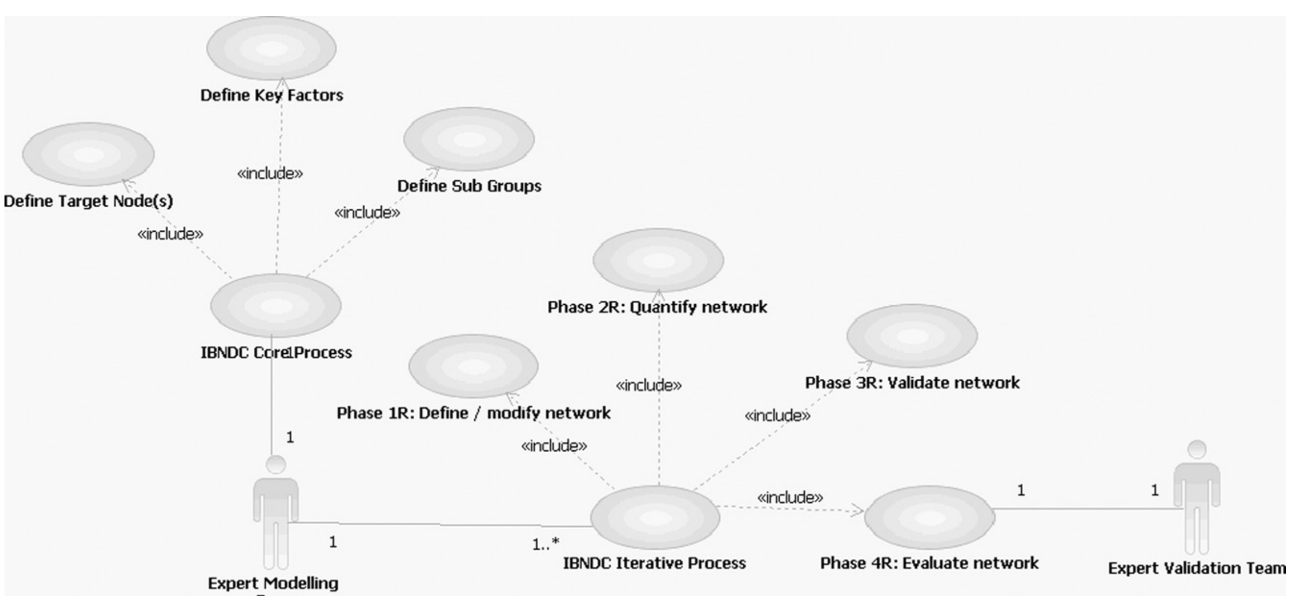


**Fig. 4.** UML use case diagram showing the interactions between the expert teams (modelling and validation) and the IBNDC processes.

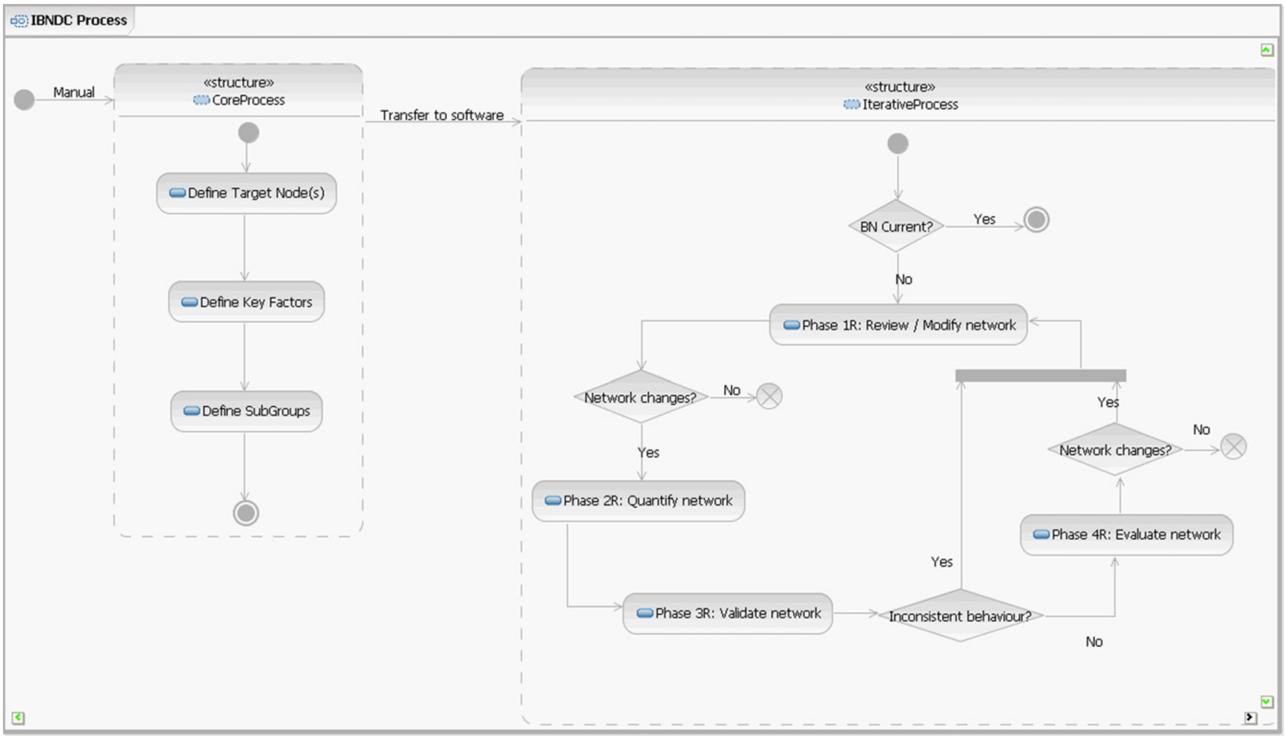


**Fig. 5.** UML activity diagram demonstrating the IBNDC processes.

parent nodes and states. Afterwards these calculated probabilities were reviewed and adjusted as directed by the experts and also as a result of the successive iterative phases in the IBNDC.

After each network had been quantified, it was tested in Phase 3R (Validate) to examine whether the predictions were consistent with known behaviour and whether the BN respected known causal relationships. This included reflection on the accuracy of predicted probabilities and whether the predictions respected expected patterns of change incurred as a result of changes in factor probabilities. The testing was primarily done using expert knowledge to interpret the observed behaviour of the network (or subnetwork) (Pollino et al., 2007b). If this was satisfactory, data conflict analysis was performed to ensure that the evidence entered was in line with the modelled structure. If there were inconsistencies, this could be due to either an error in the entered data (evidence), an error in one of the CPTs or in the directed links between the nodes. Incon-

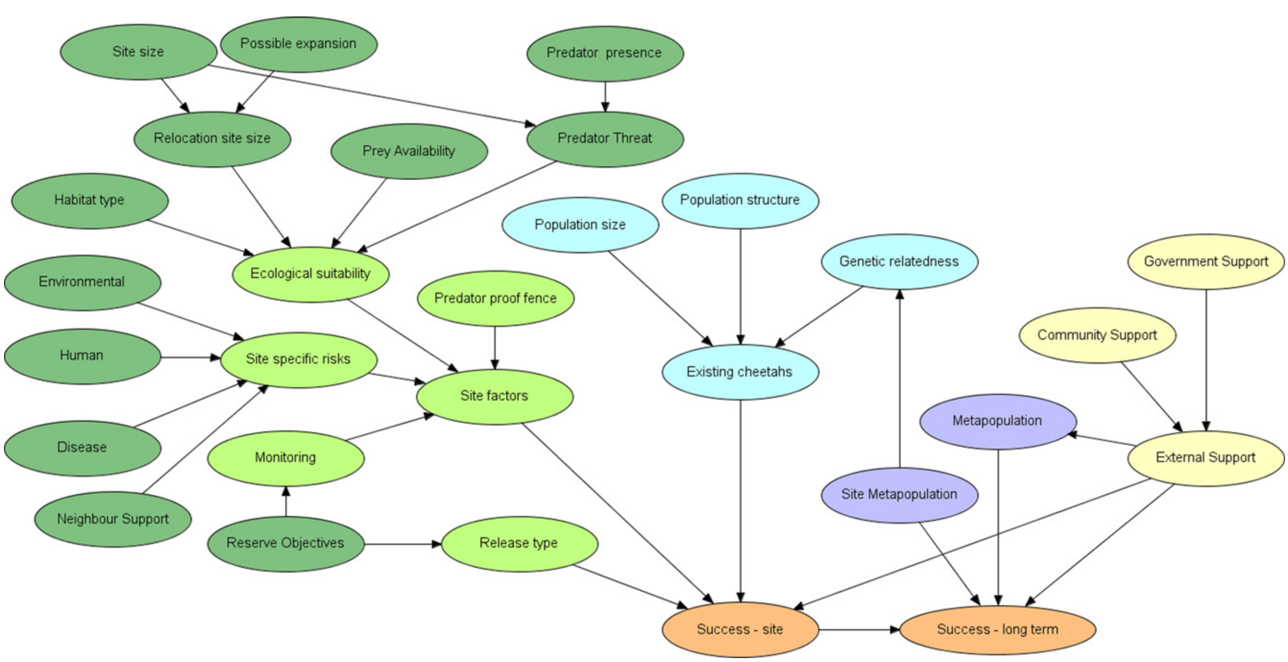


**Fig. 6.** Conceptual network for relocation into protected fenced areas showing the node groupings at the end of the Core process. The nodes were assigned to six groups; Area characteristics (green), Existing population (light blue), Management issues (blue), External support (yellow), Direct factors (light green), Survival (orange). The node descriptions are in Table 1 and several CPTs are in Appendix B. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

sistent behaviour necessitated the reassessment of nodes, states and probabilities which were addressed in the next iteration of Phases 1R and 2R. Further information on the data conflict analysis used in this study can be found on the Hugin® website (Hugin, 2007).

In addition to the validation performed at the subnetwork level, the entire network was also tested by assessing the target node behaviour in two ways: (i) using only the subnetwork end-point nodes, that is, treating each subnetwork as a single node and (ii) using the input/observation nodes, that is, the leaf nodes of the network.

In Phase 4R (Evaluate), the subnetworks were evaluated through inference (de Waal and Ritchey, 2007), scenario testing (case studies from experts) and sensitivity analysis (Pollino et al., 2007a). Evaluation through inference was done by using the BN in a predictive mode (effect on survival if the states of particular factors are specified), prescriptive mode (best level of a factor if the states of other factors are specified) and diagnostic mode (circumstances corresponding to best or worst survival) (de Waal and Ritchey, 2007). Once the final evaluation (last iteration of Phase 4R) of the subnetworks and the entire network had taken place, an external evaluation of the network by another expert panel was conducted.

**Table 1**
Nodes and states of the Protected Fenced Relocation BN (Fig. 6).

| Node | Description | States |
|---|---|---|
| Community support | Community and peer support: Farmer communities, conservation bodies, ngo's | High, Low, None |
| Disease | Catastrophy according to veterinary department. Distemper, rabies, parvo virus if present in high numbers would affect the choice of using that area as a release site. | Normal, Exceptional |
| Ecological suitability | Summary Node | Suitable, Not Suitable |
| Environmental | Disasters—floods, drought, fire | Normal, Exceptional |
| Existing cheetahs | Summary node for existing cheetah population at the site: Suitable/not suitable for introduction | Suitable, Not Suitable |
| External support | Summary node | Good, Limited, None |
| Genetic relatedness | The relatedness between existing cheetahs and the proposed introduced cheetahs | Yes, No, Unknown |
| Government support | Involves both legislation (for relocation) and implementation. The extent to which the government supports relocation activities.<br>States: No - relocations are not permitted; Limited - some support with lobbying, lack of capacity, with non-applicable or outdated legislation, legislation present but not informed; Yes - good legislation and implementation, proactive, informed, capable | Yes, Limited, No |
| Habitat type | Whether habitat is suitable for cheetah relocation | Suitable, Not suitable |
| Human | Human factors in conflict with cheetahs. Cheetahs will get in conflict when they: 1. Eat livestock/game of value 2. Perceived belief of threat to people | None, Settlement, Agricultural, Both |
| Metapopulation | Participation of all the reserves in a country-wide network of fragmented reserves | Yes, No |
| Monitoring | Direct or indirect monitoring (using GPS/satellite/VHF collars), indication of the level of monitoring in place<br>Daily: daily visuals or locations of all the cats (you have a signal and the signal is moving) direct or indirect monitoring; Less frequent: anything less than daily | Daily, Less Frequent, Absent |
| Neighbour support | Neighbouring Support for relocation by surrounding communities | Yes, No |
| Population size | The cheetah population size after relocation event | Under capacity, Within Capacity, Over Capacity, None |
| Population structure | Consider: male/female ratio, dominant coalition size, age of cheetahs currently in release site | Suitable, Adjustments, Not suitable |
| Possible expansion | Possible expansion of relocation site? | Yes, No |
| Predator presence | Presence of lions & spotted hyenas. Leopard presence taken as given | |
| Predator proof fence | Predator proof fencing of neighbouring properties or release site | Yes, No<br>No - no predator proof fence, or not maintained; Yes - well maintained |
| Predator threat | Current or future predator threat of lions and hyena. Leopards assumed present | High, Low, No |
| Prey availability | Suitable prey for cheetahs (Sufficient: self-sustaining for 2 years before re-introducing new prey) | Sufficient, Not sufficient |
| Release type | Whether hard or soft release<br>Hard: released asap from capture to new area, Soft: spends time (few weeks) in enclosure in release site before released | Hard, Soft |
| Relocation site size | Summary node for site size | Adequate, Not adequate |
| Reserve objectives | Main focus of reserve (hunting, tourism, photography) | Conservation, Ecotourism, Hunting |
| Site factors | Summary node for factors affecting site | Suitable, Not suitable |
| Site metapopulation | Site-specific participation in the metapopulation plan or indication of willingness to participate | Yes, No |
| Site size | Relocation site size min - 2000 ha; small - 5000 ha; medium - 5000–15,000 ha; large - >15,000 ha | Large, Medium, Small, Min |
| Site-specific risks | Risk factors of relocation area: including current disease levels of residing predators/livestock, injury potential due to site conditions or other problems, etc. | None, Low, High |
| Success - long term | Long-term viability of wild cheetah metapopulations, defined in accordance with the IUCN definition | Yes, No |
| Success - site | Successful relocation with respect to site. Survival of relocated cheetahs into fenced, protected areas. Individual survival 1. Capable of breeding 2. Interact socially 3. Hunt for themselves | Yes, No |

Any suggested structural and probabilistic changes by this panel were submitted for confirmation by the original expert panel responsible for creating the BN.

In the project described in this paper, discussion about the composition of the external expert panel and its role in determining the final network was deferred until the last iteration of Phase 4R. However choosing an expert review team is not an iterative process and we therefore recommend that this activity is instead undertaken as part of the *Core process* once the outcome of interest has been defined (step 1). The expert modelling team will then be able to decide on a review panel who they feel is suitably qualified to review the BN being modelled.

## 3. Results

### 3.1. Core process

The target nodes identified by the panel were short-term survival of the relocated cheetah (*Success - site*) and long-term cheetah population viability (*Success - long term*). Successful short-term survival is when recruitment exceeds adult death rate in a breeding population of cheetah during the 3 years post-release (Hayward et al., 2007). Besides this definition for short-term survival, the expert panel identified additional indicators of short-term success as the ability of the cheetah to successfully hunt prey, successful socialisation with other cheetahs and capacity to breed. For females, capacity to breed was defined as successful reproduction of a first generation; for males, it was defined as successful reproduction of the male or his coalition or his ability to establish and hold a territory for 1.5 years. Long-term population viability was defined in accordance with the IUCN definition, including successful first generation reproduction and natural recruitment exceeding deaths (IUCN, 2007).

Although many of the key factors were endorsed by both countries, the relocation events were sufficiently different to be considered independently. The consequences of relocating to an unfenced versus a fenced site not only introduced additional factors, but also negated other factors and changed interactions between some factors. Similar differences were found in considering relocation into protected versus unprotected areas. For these reasons multiple networks commensurate with four types of relocation events were required for short-term survival of the relocated cheetah, with corresponding slight changes to the network for population viability. The four relocation events were (1) relocation into fenced protected areas; (2) relocation into unfenced protected areas; (3) relocation into unfenced unprotected areas; (4) in situ relocation. We describe below the OOBN for the first relocation event into fenced protected areas. The OOBNs for the other three relocation events are shown in Appendix (A3–A5).

#### 3.1.1. Relocation into fenced protected areas

Fig. 6 depicts the conceptual network developed for relocation into protected fenced areas and Table 1 contains descriptions of the nodes for this network. The probability of survival of a relocated cheetah in a fenced protected site was designed to be directly dependent on four factors: the *Release type*, *Site factors*, the existing cheetah population (*Existing* cheetahs) and *External support* (Fig. 6). Whereas a hard release (*Release type*) sees the animal released as soon as possible after capture, a soft release involves habituating the cheetah in a boma (a temporary holding facility suitable to keep the specific predator for a period of time, prior to release or for veterinary reasons) or similar enclosure for up to 3 months and is generally accepted to be the preferred method of relocating predators (Gusset et al., 2006). Although the *Release type* can depend on the *Reserve objectives* (hunting, conservation or ecotourism), the cheetah experts indicated that current releases are almost exclusively soft in South Africa and hard in Botswana. *Site factors* refer to the suitability of the site for relocation and include the existence of predator proof fencing (*Predator proof fence*), *Site-specific risks* (*Human*, *Disease*, *Neighbour support* and *Environmental*), *Ecological suitability* (*Habitat type*, *Relocation site size*, *Prey availability* and *Predator threat*) and the type of monitoring of cheetahs (*Monitoring*) by the owner of the site. The expert team determined the frequency of monitoring to be influenced by the *Reserve objectives* with ecotourism reserves almost always having monitoring in place and most likely monitor the relocated cheetahs on a daily basis. Whereas reserves with a conservation or hunting focus, although also likely to monitor the animals, are usually not monitoring the cheetahs as frequently as ecotourism reserves. To determine the *Predator threat*, the expert team suggested that only lions and spotted hyena were considered since leopards are assumed to be always potentially present.

The expert team deemed the need to consider the suitability of the existing cheetah population (*Existing cheetahs*) with respect to the relocated animal to be a consequence of the increased management required in fenced areas (*Site metapopulation*). The *Population size* after the proposed relocation event, its *Population structure* (gender, coalitions, age) and the *Genetic relatedness* dictate its suitability. The genetic relatedness of the resident cheetah population was strongly influenced by whether the site participates or showed a willingness to participate (*Site metapopulation*) in a metapopulation plan (*Metapopulation*). The expert team argued that a metapopulation plan was an integral part of South African cheetah conservation and is particularly important for confined animals in fenced areas, but that no such plan exists for, or is relevant to, relocated cheetah populations in Botswana.

The second target node, long-term population viability (*Success - long term*), was influenced by the survival of the cheetah at the site (*Success - site*), the metapopulation plan (*Metapopulation*) and *External support* comprising both *Community support* (Non-Governmental Organisations and peer support) and *Government support*. Support from farmer communities, conservation bodies are believed by the expert team to carry a lot of weight with respect to the successful outcome of a relocation event and to the viability of the wild cheetah population. Support from the government includes the existence of positive legislation for relocation and the commitment to its implementation.

### 3.2. Iterative process

Iterations of the four phases in this process were performed for each of the subnetworks after the outcomes of interest (target nodes) were clearly defined and the subnetworks conceptualised. The subnetworks in the protected fenced relocation BN have summary nodes and are colour-coded, for example (Fig. 6) the Ecological suitability subnetwork has nodes *Habitat type*, *Site size*, *Relocation site size*, *Possible expansion*, *Prey availability*, *Predator presence* and *Predator threat*, and summary (or child) node *Ecological suitability*.

#### 3.2.1. Phase 1R (define/modify) and Phase 2R (quantify)

A BN is quantified by means of probability tables (CPTs). Each node in the network has a probability table associated with it and the table is defined by the parent nodes feeding into the particular node (Jensen and Nielsen, 2007). For the protected fenced network, a total of 520 probabilities were elicited by the expert panel and the largest probability table was *Site-specific risks* with 96 probabilities. Several CPTs for this network are included as an Crooks et al., 1998; Durant, 2000; Durant et al., 2004; Laurenson et al., 1995; Merola, 1994; appendix to this paper, including two of the subnetworks (Ecological suitability and Site factors) for the OOBNs created for the different types of relocation events.

**Table 2**
Evidence sensitivity analysis for posterior network (Protected Fenced Relocation BN), showing calculated entropy.

| | |
|---|---|
| *Success - long term* | *0.1983* |
| *Success - site* | *0.3555* |
| Human | 1.1922 |
| Population size | 1.0889 |
| Population structure | 1.0297 |
| Predator threat | 1.0097 |
| Existing cheetahs | 0.9700 |
| Government support | 0.8979 |
| Reserve objectives | 0.8979 |
| Site-specific risks | 0.8547 |
| Monitoring | 0.8207 |
| Community support | 0.8018 |
| Site size | 0.8018 |
| Existing cheetahs | 0.6908 |
| Possible expansion | 0.6730 |
| Metapopulation | 0.6720 |
| Ecological suitability | 0.6559 |
| Predator presence | 0.6474 |
| Relocation site size | 0.5792 |
| Site factors | 0.5425 |
| Genetic relatedness | 0.4314 |
| Release type | 0.3669 |
| Disease | 0.3251 |
| Environmental | 0.3251 |
| Neighbour support | 0.1985 |
| Site metapopulation | 0.1985 |
| Habitat type | 0.0000 |
| Predator proof fence | 0.0000 |
| Prey availability | 0.0000 |

The two end points of the BN are in italics at the top of the table and are reference points for the other nodes.

**Table 3**
Mutual information between the target node (*Success - site*) of the Protected Fenced Relocation BN and the other variables.

| | |
|---|---|
| Site factors | 0.1041 |
| Ecological suitability | 0.0657 |
| Existing cheetahs | 0.0557 |
| Predator threat | 0.0274 |
| Predator presence | 0.0199 |
| Relocation site size | 0.0175 |
| Population structure | 0.0121 |
| Population size | 0.0113 |
| Monitoring | 0.0098 |
| Site size | 0.0030 |
| Reserve objectives | 0.0027 |
| Release type | 0.0019 |
| Genetic relatedness | 0.0012 |
| Site-specific risks | 0.0010 |
| Possible expansion | 0.0005 |
| Site metapopulation | 0.0002 |
| External support | 0.0020 |
| Disease | 0.0001 |
| Metapopulation | 0.0001 |
| Human | 0.0001 |
| Government support | 0.0001 |
| Environmental | 0.0000 |
| Community support | 0.0000 |
| Neighbour support | 0.0000 |
| Habitat type | 0.0000 |
| Prey availability | 0.0000 |
| Predator proof fence | 0.0000 |

### 3.2.2. Phase 3R (validation) and Phase 4R (evaluation)

Validation and evaluation of the networks were done by the workshop expert panel using case studies of known relocation sites, history of relocation events at those sites and running 'what if' scenarios to verify that the model is behaving in accordance with known situations. The networks were also reviewed by two cheetah experts in Botswana who were not part of the workshop panel developing these relocation networks.

Moreover it is important to identify those model parameters for which variations in CPT values produce the greatest changes in the network end points (parameter sensitivity). Further attention must be paid to these nodes to ensure that their CPTs are precise (Laskey, 1995; Pollino et al., 2007b). The sensitivity of the target nodes to variations in the evidence entered into the BN also needs to be assessed (evidence sensitivity) (Varis and Kuikka, 1999; Bednarski et al., 2004; Pollino et al., 2007b). Sensitivity analysis was therefore performed on the two end points, success of a relocation event (*Success - site*) and long-term population viability (*Success - long term*). We discuss here sensitivity analysis for the protected fenced network.

Evidence sensitivity measures the degree of variation in the BN's posterior distribution resulting from changes in the evidence being entered in the network. Ranking the evidence nodes accordingly assists the expert in targeting future data collection and in identifying any errors in the BN structure or CPTs (Pollino et al., 2007b).

Two popular ways in which to measure evidence sensitivity are entropy and mutual information (Pollino et al., 2007b). Entropy, $H(x)$, measures the randomness of a variable and is calculated as follows (Pearl, 1988; Korb and Nicholson, 2004; Pollino et al., 2007b):

$$H(X) = -\sum P(x)\log P(x) \quad (1)$$

where $P(x)$ is the probability distribution of $X$:

The entropy values for the protected fenced BN are shown in Table 2. These results show that the type of neighbouring property (*Human*) and the composition of the existing cheetah population at the site (*Existing cheetah population*, *Population size*, *Population structure*) as well as the threat posed by predators (*Predator threat*) at the relocation site cause the largest variation in the BN's posterior distribution.

The other measure of evidence sensitivity is mutual information $I(X,Y)$, which gives an indication of the effect that one random variable, $X$, has on another variable, $Y$, and is calculated as follows (Korb and Nicholson, 2004; Pollino et al., 2007b):

$$I(X, Y) = H(X) - H\left(\frac{X}{Y}\right) \quad (2)$$

The mutual information results between the node representing the success of a relocation (*Success - site*) and the other factors in the protected fenced network are shown in Table 3. This table clearly shows that the factors at the site (*Site factors*) have the largest effect. This node is a function of the presence of predator proof fencing for neighbouring properties (*Predator proof fence*), the extent of *Monitoring* of the released cheetahs, any inherent risks at the site (*Site-specific risks*) and the *Ecological suitability* of the site. The latter is also calculated to have the next largest effect, followed closely by the Existing cheetah population at the site (*Existing cheetahs*).

Next the protected fenced BN was inspected for parameter sensitivity using one way sensitivity analysis where one of the parameters is varied (*Predator presence*) while keeping all the others fixed and then measuring the variation in the output parameter (*Success - site*) (Bednarski et al., 2004). To do this a sensitivity function is required for the output probability $f(x)$ in terms of the parameter, $x$, being varied. This sensitivity function is defined in Eq. (3) below and is the quotient of two linear functions in the parameter being varied (Van der Gaag et al., 2007):

$$f(x) = \frac{\alpha x + \beta}{\gamma x + \delta} \quad (3)$$

where $\alpha$, $\beta$, $\delta$, and $\gamma$ are constants built from the parameters which are fixed.

The sensitivity value of the parameter $x$ and the target probability can be obtained by taking the first derivative from the sensitivity

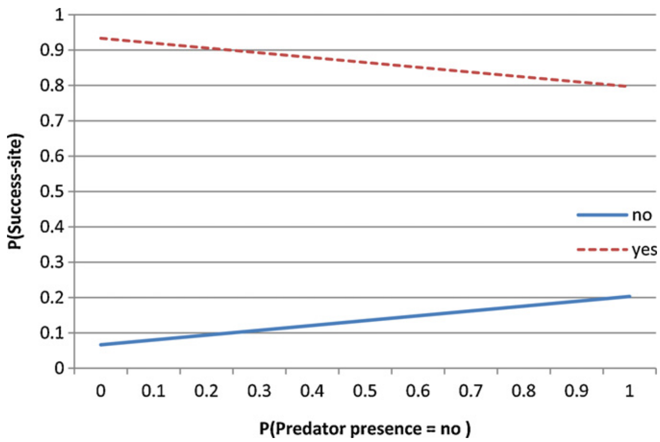


**Fig. 7.** Parameter sensitivity graph showing the slope of change for high and low predator presence at the relocation site. The observed posterior probabilities for a successful relocation event (*Success - site*) are shown on the *y*-axis and the changes in conditional probabilities for predator presence are on the *x*-axis.

(Laskey, 1995; Van der Gaag et al., 2007) and is given by the following equation:

$$f'(x) = \frac{\alpha\delta - \beta\gamma}{(\gamma x + \delta)^2} \quad (4)$$

Fig. 7 below shows the sensitivity of the success of a relocation event (output probability) to variations in the values for no predator presence.

Similar to successful relocation at a site, the long-term cheetah population viability is also sensitive to changes in the presence of predators. Furthermore government support, community support and the existence of a metapopulation plan play an important role for long-term viability whereas for a single successful relocation, they were not particularly relevant. Importantly, the long-term viability is most sensitive to the success of the individual relocation events.

In the unfenced networks a successful relocation (*Success - site*) was still sensitive to *Predator presence*, but not the same extent as in fenced areas. In addition, support from the government (*Government support*) and the wider community (*Community support*) featured more prominently than was the case in fenced areas. The success of a relocation event is sensitive to changes in the distance of human settlements (*Distance from settlements/farms*) to the relocation site as well risk factors in the relocation area (*Site-specific risks*) that could cause disease and injuries as well as other adverse effects on the relocated cheetahs. These site-specific risks include traditional healers, land claims, disease, old agricultural land and floods.

Fig. 8 illustrates field testing of the network involving using a case study derived from the experts' experience. The target nodes (*Success - site* and *Success - long term*) need to reflect expected predictive patterns and/or known outcomes from the case study. The experts then kept all states of the factors the same, except having predators present. The change in probability of success of the two critical events was noticeable with relocation success dropping from 32.56% to 10.19% and long-term viability dropping from 26.93% to 8.43%. This also endorses earlier findings from sensitivity analysis that *Predator presence* influences the probability of success in a very significant manner.

## 4. Discussion

This study investigated the use of a Bayesian network model to integrate, structure, and clarify human expertise on a composite problem, the relocation of cheetahs in two southern African countries using an original heuristic method, an iterative development cycle (IBNDC). The expected advantages are the consolidation of the resulting overall BN implementation and a continuous improvement of the model with incoming expertise from new case studies. This approach has been developed using a combination of several existing BN types and suggests a new approach to implementing BNs in a multi-expert and multi-field domain.

While Bayesian Networks are not a new approach to ecological modelling, deriving their structure is particularly difficult, as is populating them with data. We outline a more iterative way of doing so, that is conducive to ideas on adaptive management. The IBNDC complements the suggested three-level BN approach to modelling by Marcot et al. (2006) and focuses on the iterative nature of BN modelling. Essentially the IBNDC is always a work in progress with the first step in the iterative process checking whether the BN needs modifying in light of new research and information. Therefore any version of the network is a snapshot of the most current expert knowledge and evidence available at that time and as new evidence and knowledge come to light, the BN model is continually revised and refined. Information on cheetah relocations is sparse, the benefits of various techniques are still being investigated and new information on relocation events is continually becoming available especially with increased monitoring in place. For these reasons the relocation BN was ideally suited to the IBNDC

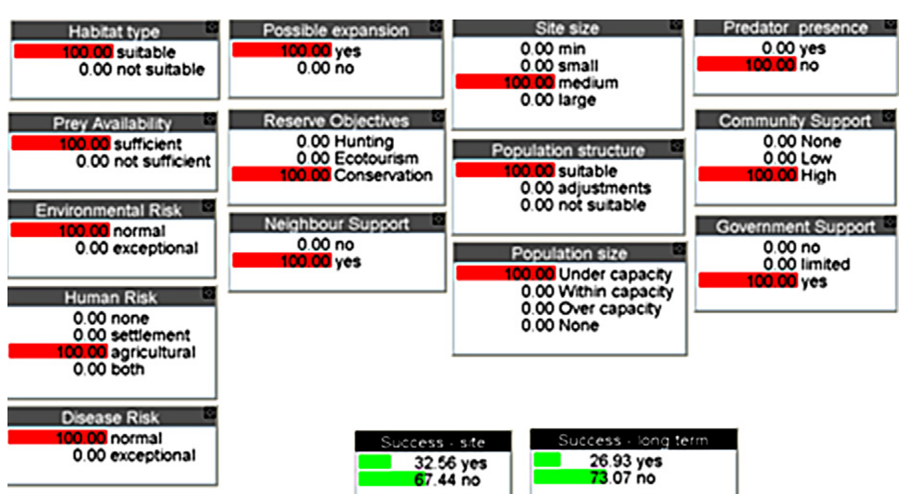


**Fig. 8.** Predictive testing—case study 1.

process. Once the Bayesian network has successfully completed the IBNDC procedure using the available current expert knowledge and information, it can be employed as a management support tool.

The areas into which the two countries are able to relocate problem cheetahs differ significantly and certain factors considered important in certain situations may be less important or totally irrelevant in other situations. Pinpointing the factors and subnetworks pertinent to all BNs was important to the understanding of the crucial factors in cheetah relocations and would be candidates for consideration in other predator relocations. Furthermore the relocation events were considered in the context of the wider metapopulation viability. Some factors central to the success of a relocation event may also play a significant role in the metapopulation viability. Particularly in South Africa, management of the metapopulation of cheetahs in small fences reserves is becoming a challenge. Due to the small size of populations inside fenced reserves, intensive management is required to prevent inbreeding and local overpopulation, and to ensure long-term sustainability of the cheetah metapopulation. Although the cheetah relocation BN demonstrates an exposition of the IBNDC to cheetah conservation, relocation is just one option among a suite of tools used to resolve human-cheetah conflict in southern Africa.

There are several possible applications of BNs in a conservation management support environment, such as:

- Calculating risk associated with management decisions.
- A tool for negotiation, for example when consulting with reserves which are suitable as relocation sites.
- Illustrating trade-offs between various relocation sites and reserves.
- Training tool to introduce newcomers to the management process of wild cheetah relocations.

The IBNDC process prioritises future data collection as part of the iterative process thereby facilitating continuous improvement of this tool. While relocations can be successful in a specific reserve, they require intensive and expensive management to be viable in the long term. The emphasis should be on conserving cheetahs in situ, and as indicated above, in this situation the BN can be used as an effective negotiation tool with landowners and stakeholders. The IBNDC procedure can also be used for the development of other useful management tools to guide decision making in the management of the cheetah metapopulation.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2009.11.012.

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