Chapter 14
Bayesian Networks for Understanding Human-Wildlife Conflict in Conservation

Jac Davis, Kyle Good, Vanessa Hunter, Sandra Johnson, and Kerrie L. Mengersen

Abstract Human-wildlife conflict is a major threat to survival and viability of many native animal species worldwide. Successful management of this conflict requires evidence-based understanding of the complex system of factors that motivate and facilitate it. However, for many affected species, data on this sensitive subject are too sparse for many statistical techniques. This study considers two iconic wild cats under threat in diverse locations and employs a Bayesian Network approach to integrate expert-elicited information into a probabilistic model of the factors affecting human-wildlife conflict. The two species considered are cheetahs in Botswana and jaguars in the Peruvian Amazon. Results of the individual network models are presented and the relative importance of different conservation management strategies are presented and discussed. The study highlights the strengths of the Bayesian Network approach for quantitatively describing complex, data-poor real world systems.

Keywords Cheetah · Botswana · Jaguar · Peru · Amazon · Conservation · Bayesian network · Human-wildlife conflict

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14.1 Introduction

Among the 105,732 species listed in the update to the International Union for the Conservation of Nature (IUCN) update to the Red List of Threatened Species, over a quarter (28,338) are reported to be threatened with extinction [11]. The single most important threat identified in the report is humans. This threat is realised through a range of activities, including but not limited to over-exploitation of the species, habitat loss, spread of disease, environmental mismanagement associated with human activities, and conflict.

In this study, we focus on this last factor, namely conflict, and its impact on a particular set of species, namely wildlife. Although human-wildlife conflict includes both negative impacts of wildlife on humans, and of humans on wildlife (WPC Recommendation [35]), for the purposes of the current paper we confine our attention to direct negative impacts of human behaviour on wildlife.

Many threatened wildlife species have home ranges that extend into modified urban, agricultural and industrial landscapes. The requirements of urban, agricultural and industrial land uses often conflict with the requirements of wildlife biodiversity conservation, contributing to threatening processes which drive wildlife population declines. Proximity of threatened wildlife to urban and rural human populations also leads to diverse and often polarised societal attitudes towards wildlife, thereby threatening agents and conservation efforts to save threatened wildlife. The need to reconcile diverse societal attitudes and conservation imperatives further complicates decision-making processes and conservation efforts.

Substantial resources have been committed to understanding the factors associated with threatened wildlife species, and although resource managers recognize that these factors range across ecological, biological, physical, social and economic perspectives, research and management efforts are typically confined to specific issues. A major reason for this is because it is often difficult to consider the multitude of factors in a coherent, transparent manner.

One approach to modelling the many facets of human-wildlife conflict is through a Bayesian Network (BN). BNs are increasingly being used for ecological, environmental and conservation modelling, among many other applications [8, 14–16, 17]. A key advantage of this method is that it can integrate quantitative information from a variety of sources, including expert knowledge [15]. This is advantageous when there is a lack of observed data, which is the case for many situations involving threatened species. In the case of human-wildlife conflict, a BN based on expert knowledge can help to identify the major factors that are associated with this conflict and their relative impact, as well as quantitatively evaluating the impact of changes to one or more of these factors in light of all the other influences in the system. In this manner, the BN can also be used to prioritise interventions that support the species' continued survival.

In this chapter, we present BN models for two threatened wildlife species, namely cheetahs in Botswana and jaguars in the Peruvian Amazon. Each of these models was developed and quantified using expert information. The intention of these models was to understand the viability of the species from a multi-faceted perspective that not only crosses disciplines but integrates the diversity of stakeholder perspectives. We focus on bringing together the ecological, biological, societal and economic pressures on, and opportunities for the species, in order to facilitate decision-making and conservation initiatives. In addition to illustrating the probabilistic assessments that arise from such models, we also highlight some of the similarities and differences between the factors that were considered to be important for each species.

Cheetah numbers in Botswana are declining, partially as a result of human-cheetah conflict [9, 33]. Human-cheetah conflict can take many forms. Some of the most common are farmers killing cheetahs to protect livestock [25], out of fear for their personal safety, or hunting for skins, meat, and other cheetah products. The scale of this conflict has prompted calls for interventions to prevent local people from killing cheetahs at an unsustainable rate [31]. Implementing these interventions, however, is not a trivial matter, and considering the social context of the intervention is vital [24]. Rural villages are made up of people from either the majority ethnic group (the *Tswana*), which has a strongly hierarchical structure, or minority ethnic groups, who are marginalised and very poor. The livelihoods of rural people, particularly those from these minority groups, are very dependent on hunting and gathering veldproducts, and may be highly impacted by wildlife management interventions [29].

Jaguars are a declared near-threatened species (IUCN) which means that they have the potential to go extinct sometime in the near future. Although it is acknowledged that prime jaguar habitat is the Amazon rainforest, remarkably little is known about jaguar occupancy or abundance in many parts of the jungle. A case in point is the northern part of Peru. Although Peru has the second largest remaining tract of rainforest in the world and an extensive series of national parks and reserves, there have been very few formal studies of jaguars in these areas. Key reasons for this paucity of data include the time required to reach study sites, difficulties in travelling through the jungle, the elusiveness of the target animal and the need to engage with the indigenous residents of the forest.

The chapter proceeds as follows. Section 14.2 provides a description of the BN methodology used to quantitatively evaluate the factors associated with human-wildlife conflict. This is described in general and then for each study in particular. Section 14.3 provides a summary of the results of the BN modelling for each case study, followed by an illustration of the types of inferences that can be made on the basis of these models. These inferences include identification of priority factors and assessment of the sensitivity of the network to hypothetical scenarios of interest. The chapter concludes with a discussion in Sect. 14.4.

14.2 Methods

14.2.1 Bayesian Networks

A Bayesian Network (BN) modelling approach was used to construct a systems model for describing the set of interacting factors that influence the viability of the target wildlife species. The BN model is often represented graphically, with the variables depicted as nodes (circles) and the interactions depicted as directed arrows (arcs). Probabilistic quantification of the model follows, in which the probabilities associated with each factor are conditional on the factors that impact on it (i.e. the parent nodes, connected to the node of interest by directed arrows). These probabilities can be based on a range of available information sources, including observational or experimental data, estimates from published literature or previous studies, expert judgement and so on. Although continuous probability distributions can be employed, it is common practice to discretise the corresponding variable, thereby creating a BN in which each node is quantified by a marginal probability table if it has no parents or a conditional probability table otherwise. The advantages of such a representation include fast computation of marginal probabilities for nodes of interest (including the final outcome node) based on all of the other nodes in the model, and common representation of information as probabilities despite its source.

By evaluating the probabilities in the BN, the model can be used to understand the relative impact of different factors on key nodes in the network, and importantly on the overall outcome node. Sensitivity analyses and scenario assessment can also be undertaken by modifying the underlying marginal and conditional probability tables appropriately. Using the Bayesian formulation, it is also possible to identify conditions for optimum outcomes.

14.2.2 Cheetah Study

Information for the BN for the cheetah case study was gathered via a workshop with twelve experts in cheetah conservation. The experts included local conservationists and ecologists, experts in cheetah biology and ecology, and government agents knowledgeable about relevant policy. The workshop was held over 4 days in Gaborone, the capital city of Botswana.

The BN network structure and the corresponding set of conditional probabilities were elicited using a structured approach that had been validated in other wildlife conservation BN studies [20, 27, 32]. At the workshop, the experts were asked to identify target nodes for the network (the primary outcomes of the model), and then to list all relevant factors that may influence these nodes. The final set of factors and the directed relationships between them was then agreed between the group members via a Delphi selection approach. Finally, the states of the nodes were identified and the underlying conditional probability tables populated, in an iterative process similar to that described in Johnson et al. [15].

14.2.3 Jaguar Study

The initial BN for this study was developed and quantified based on a structured interview with three members of the project team: the leader of a local conservation foundation, an international environmental journalist and a local indigenous representative. The first two members of this group were chosen because they had knowledge of international activities regarding the environment and jaguar protection, close links with the indigenous residents and established links with relevant local and state government agents responsible for the area. The local representative was chosen because he had spent many years living in the deep jungle as well as in the village, and he was highly knowledgeable about the area, the forest and jaguars in the region. As for the cheetah study, the network structure and the corresponding set of conditional probabilities were elicited using a well-tested structured approach.

The draft BN was then refined using results of a survey administered to local indigenous residents in a number of villages in the region. The aim of the survey was to obtain information about jaguar encounters and conflict, perceived trends in jaguar numbers in the past and future, usage of the forest and attitudes with respect to health, culture, environment, food and other benefits, and small and large scale forest clearing and industrial activities such as mining. The survey design and instrument broadly followed that developed by Meijaard et al. [28] for a study of orangutans and attitudes to the forest in Kalimantan, Indonesia, and was conducted in the form of questionnaires administered to local people through personal interviews. The questionnaire was initially drafted in English and subsequently translated into the local language. By necessity, respondents were not chosen randomly. People with a range of duties in the village were interviewed, with a preference for those who had knowledge about local wildlife, in particular jaguars. Steps were also taken to reduce desirability bias and recall bias [1, 28, 30]. The reliability of a respondent's responses about jaguars was determined by asking respondents to identify nine mammal species from a set of photographs, including a number of locally occurring large cat species. Only those respondents who were deemed to be sufficiently reliable were included in the present study.

The refined BN was then presented to and ratified by government representatives in Lima.

14.3 Results

14.3.1 Case Study BNs

14.3.1.1 Cheetahs

The following factors were agreed by the group of experts as important factors in human-cheetah conflict.

Government factors: Governments can affect human-cheetah conflict through enacting key policies, such as commercial hunting laws and conservancies. Governments may also be influenced by international pressure, NGOs, and pressure from citizens who favour cheetah conservation.

Economic factors: Botswana covers a vast area, and is sparsely populated [4], prohibiting timely responses to calls for assistance with cheetahs. Therefore, farmers may take it upon themselves to kill problem cheetahs, rather than waiting for them to be captured and relocated. Since the viability of wild cheetah populations depends on the survival of adult members, it is important that farmers are encouraged not to kill cheetahs to protect their livestock. Other sources of livestock protection, and sustainable management programs, may thus provide economic benefits to decreasing human-cheetah conflict. Farmers, and rural people, are directly affected by the presence of wild cheetahs and likely to be the target groups of interventions aiming to reduce conflict. Therefore, conservation strategies must consult with and engage the local community, take care to comply with village etiquette and politics, and protect disadvantaged members of the community.

Education factors: Cheetah education and rehabilitation programs, and improved access to these programs and facilities, would serve to reinforce other management programs. Rehabilitation of orphaned cheetahs can play an important role in wildlife education in general, and in knowledge of cheetahs in particular. Short- and long-term conflict may be influenced by education strategies aimed at the public such as media and information stalls, farmer education through workshops and site visits, or youth education through training teachers, distributing materials on cheetah conservation or school talks.

The expert group convened to develop the Cheetah BN agreed that interventions may have different impacts in the short and long term. Therefore, the network was designed to predict two main outcomes: a short term decrease in human-cheetah conflict, and a long-term decrease in human-cheetah conflict. The relationships between the factors and these two outcomes are presented in Fig. 14.1. Corresponding subnetworks underpinning some of the major nodes are shown in Fig. 14.2.

14.3.1.2 Jaguars

The three key factors affecting the viability of the jaguar in the wild were determined to be related to human impacts, prey insecurity and habitat loss. These are highly interdependent, as indicated in the BN model described and depicted below.

Four key human impact factors were identified, namely hunting jaguars, monitoring, human settlement and illegal logging. Hunting jaguars was in turn affected by levels of official corruption, effective policing and effective monitoring, with the latter influenced also by effective international monitoring. Human settlement was perceived to be both a benefit and a threat depending on the nature of the settlement, with indigenous villagers potentially protecting or killing the species. Growth in human settlement was perceived as a threat and was in turn affected by squatting, which is a major problem in the Amazon forest since these people are less likely to

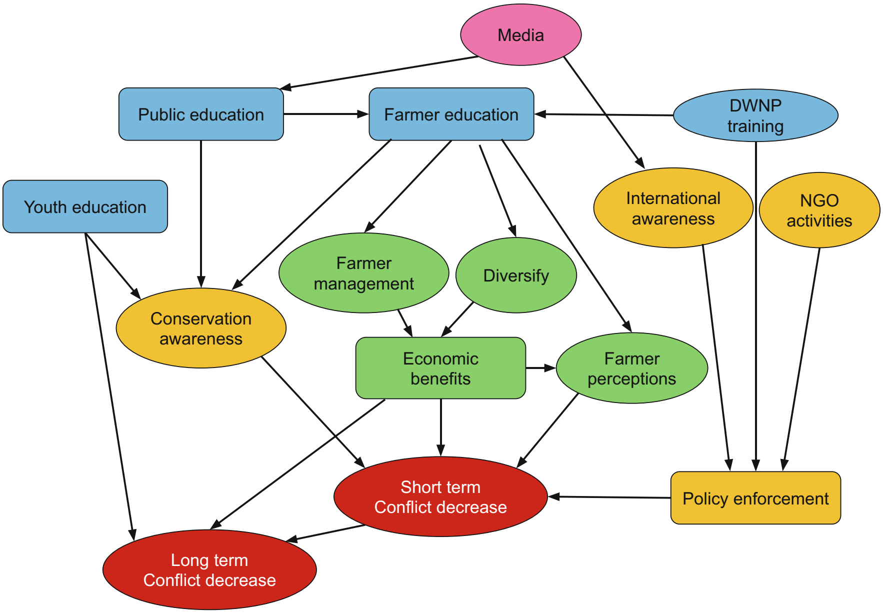

Fig. 14.1 Bayesian network for predicting and managing human-cheetah conflict in Botswana

have a history of co-existence with forest animals such as the jaguar. Illegal logging, which is acknowledged to be one of the most serious factors affecting the forest, was also influenced by effective policing.

Four key factors affecting prey insecurity were also identified. Although one of these, namely weather variability, was not human-induced, the other three were due to human activity. These included illegal logging, hunting for bush meat and harvesting a major forest fruit, aguaje, on which many wildlife species rely. The amount of illegal logging was perceived to be strongly influenced by the degree of effective policing; hunting for bush meat was influenced by human settlement, and aguaje harvest was influenced by economic development.

Drivers of habitat loss were reported to include illegal logging, aguaje harvest (since often the entire tree is cut down to access the fruit), weather variability, agriculture and pollution. The latter was believed to be a major factor and associated with petroleum production and exploration, which were driven by economic development.

The quantified human-jaguar BN is displayed in Fig. 14.3. The figure shows the marginal probabilities derived from the set of conditional probabilities for each node.

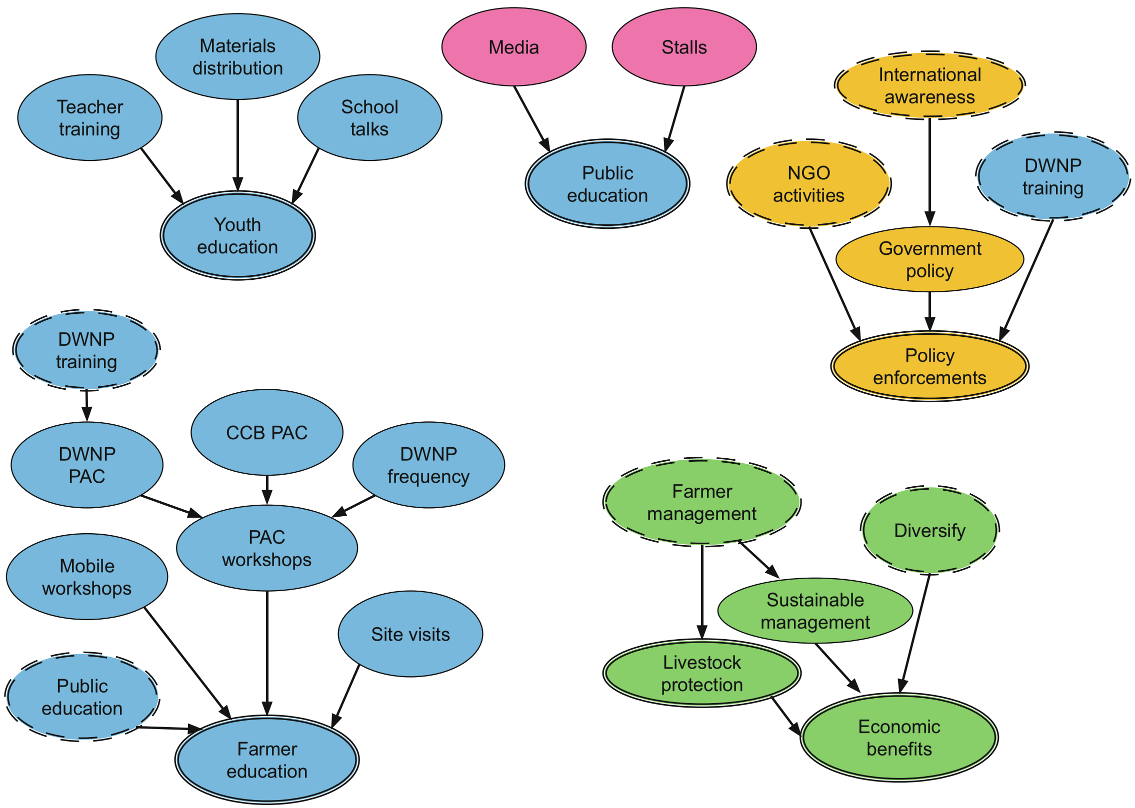

Fig. 14.2 Clockwise from top left, sub-network for youth education, public education, policy enforcements, economic benefits, and farmer education

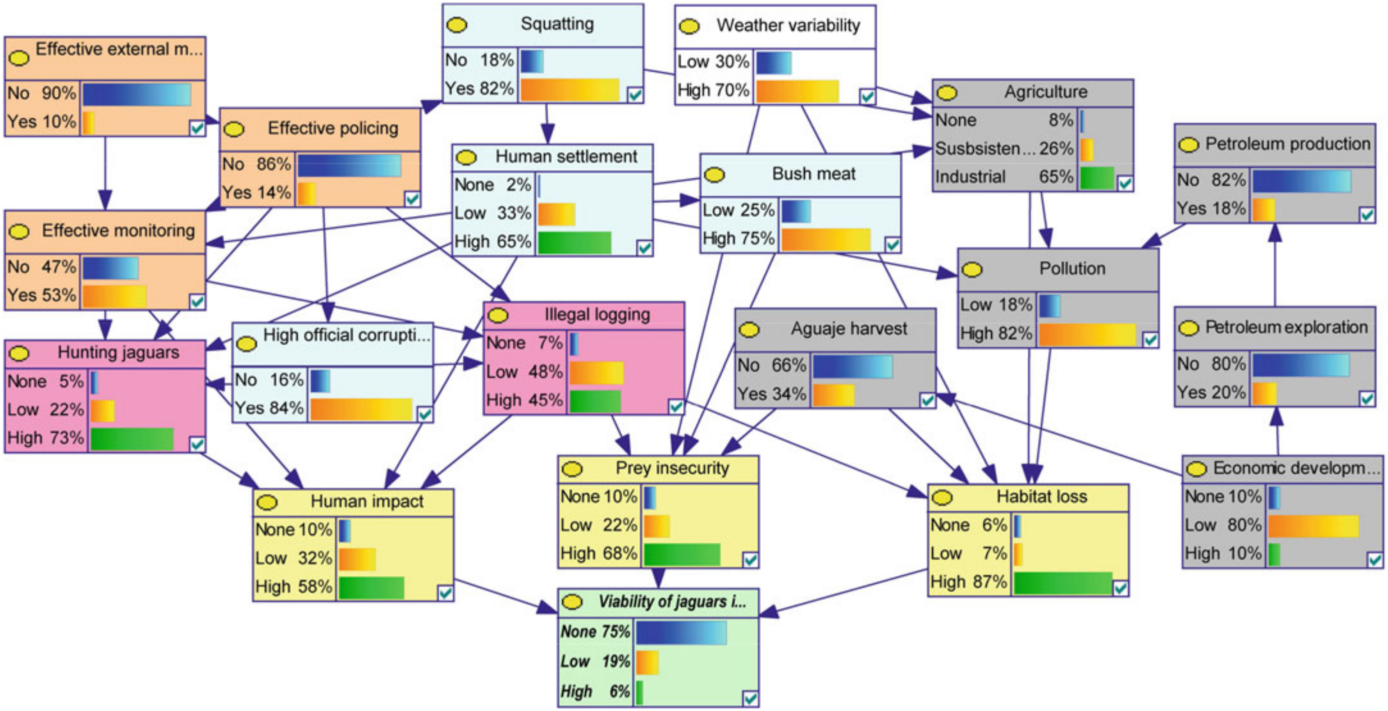

Fig. 14.3 Bayesian network for probabilistically describing the set of interacting factors that influence the viability of jaguars in the Peruvian Amazon. The truncated names of nodes are Effective external monitoring (top left), High official corruption (mid left), and Viability of jaguars in the wild (terminal node)

14.3.2 *Inferences Based on the BN*

14.3.2.1 Cheetah Case Study

We employ the cheetah case study to highlight inferences that can be made based on the probabilities determined in the BN, as well as the sensitivity of the outcome—the viability of cheetahs in the wild—to specified changes in the system.

The cheetah BN structure revealed four direct predictors of decrease in human-cheetah conflict over the long term: government policy, youth education, economic benefits, and decrease in short-term conflict. Each of these factors was in turn influenced by others in the network.

The BN model provided a set of probabilities—the probability that over the long term, human-cheetah conflict would decrease at a high rate, a low rate, or not at all—conditional on the state of the whole network system. An example of one of the conditional probabilities is presented in Fig. 14.4; plots of the other conditional probability tables are given in the Appendix.

When all factors are optimised—youth education is high, there is a high decrease in short-term human-cheetah conflict, government policy protecting cheetahs is present, and economic benefits to decreasing conflict are high—then the overall probability of a high decrease in long-term human-cheetah conflict is high, as would be expected. An observation of the other conditional probability plots allows us to

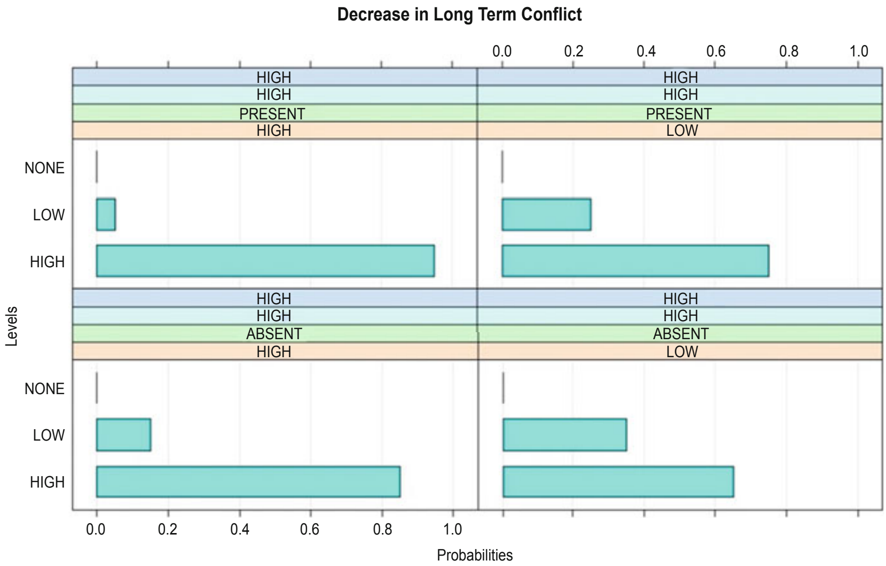

Fig. 14.4 Exemplar representation of the conditional probability table for decrease in long term conflict with cheetahs in the wild in Botswana, based on the levels of the four parent nodes, respectively Youth Education, Short Term Conflict, Government Policy and Economic Benefits

examine more complex scenarios. For example, when short-term conflict decrease is low, and economic benefits are low, but youth education is high and government policy is present, then the probabilities of a low or high decrease in human-cheetah conflict are roughly equal, and when government policy is absent, a low decrease in conflict becomes the most likely outcome.

Examining the network reveals that, surprisingly, if youth education is low and government policy is absent, but short-term conflict decrease is high, and there are high economic benefits to decreasing conflict, then it is very likely that the decrease in human-cheetah conflict will be high in the long term. Furthermore, if government policy is present but all other factors are low, it is very likely that there will be no decrease in human-cheetah conflict in the long term. Together, these scenarios suggest that government policy is less impactful in the long term than other strategies for decreasing human-cheetah conflict.

14.3.2.2 Jaguar Case Study

We employ the jaguar case study to illustrate the ability of the BNs to provide a quantitative assessment of the sensitivity of the network outcomes to hypothetical scenarios.

Based on a sensitivity analysis of all nodes in the system, the strongest links in the jaguar BN were determined to be between the following pairs of factors: Economic development and Aguaje harvest; Effective monitoring and Illegal logging; Human settlement and bush meat; Human settlement and agriculture; Petroleum exploration and petroleum production; Effective policing and squatting; and Effective external monitoring and effective policing.

Six scenarios were evaluated. The first four involved modifying in turn the three nodes that were parents of the target node (Viability of jaguars in the wild), i.e. Human impact = No, Prey insecurity = No, Habitat loss = No, and all three factors = No, respectively. All other factors remained unchanged. The results of these evaluations are shown in Fig. 14.5. The last two scenarios comprised two positive management decisions: 100% effective monitoring and no aguaje harvest; and no official corruption or illegal logging. The results of these evaluations are shown in Table 14.1.

14.4 Discussion

A Bayesian network model was used to synthesise citizen knowledge in a wide variety of domains concerning human-wildlife conflict with two iconic threatened species in two very different locations, namely the plains of Botswana and the jungle of Peru. In each study, the BNs were developed and quantified using the combined expertise from government agents, ecologists and conservationists. In both cases, the BNs reflected the most important factors perceived by the group, the directed

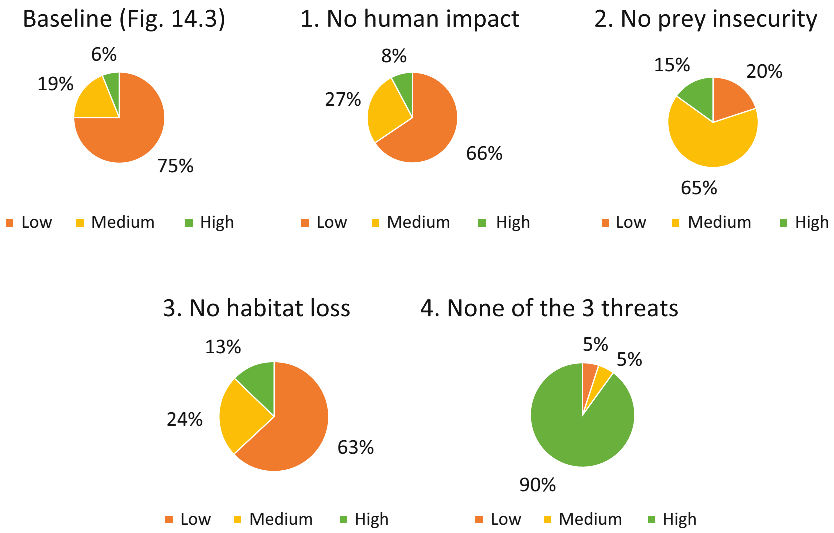

Fig. 14.5 Results of first four hypothetical scenarios for the jaguar case study, varying the three parent nodes of the target node. Last scenario is best case (no human impact, prey insecurity or habitat loss)

connections between these factors, and the quantitative evidence relating to the behaviour of each factor in light of the other impacting influences. Importantly, the BNs were able to describe and predict the outcomes of multiple management strategies at once, incorporating the kind of complex and multifaceted solutions needed to effectively address human-wildlife conflict [3, 7, 19, 21, 23].

No data exist against which to validate the predictions of the BNs developed and reported in this study. However, the system of factors identified by the BNs are echoed in conservation papers elsewhere. For example, in the cheetah study, the experts separated the short-term and long-term effects of conflict management strategies, a distinction which is increasingly recognised as important in conservation biology in general, and human-wildlife conflict in particular [6]. In addition, social factors were well-represented in both BNs, and have been identified as essential to successful conflict management for cheetahs, jaguars and other species [2, 6, 11, 18, 21, 22, 36].

For both systems, data on the respective human-wildlife conflict are scarce and difficult to access, but using the BN allows for the knowledge hidden in experts' heads to be extracted, quantified, and synthesised across domains. The BN supports decision making by identifying most influential factors that impact on the outcome of interest, and allowing various scenarios to be simulated before they are implemented. In this way the BN can provide a key planning tool for managing human-wildlife conflict for big cats in particular, and for other wildlife species in general.

Table 14.1 Results of last two hypothetical scenarios representing positive management decisions for jaguar conservation: Scenario 5 (100% effective external monitoring, no aguaje harvest) and Scenario 6 (no official corruption, no illegal logging)

Factor	Human impact	Prey insecurity	Habitat loss	Hunting jaguars	Viability of jaguars in the wild
Baseline (Fig. 14.4)	0.10, 0.32, 0.58	0.10, 0.07, 0.68	0.06, 0.07, 0.87	0.05, 0.22, 0.73	0.75, 0.19, 0.06
Scenario 5	0.17, 0.32, 0.50	0.12, 0.21, 0.67	0.06, 0.09, 0.85	0.07, 0.37, 0.57	0.73, 0.21, 0.06
Scenario 6	0.41, 0.32, 0.37	0.44, 0.28, 0.28	0.15, 0.22, 0.63	0.08, 0.67, 0.25	0.40, 0.45, 0.15

Probabilities pertain to Low, Medium and High states of the corresponding node in the BN network displayed in Fig. 14.3

The BNs presented here are limited in scope; for example, they do not account for larger forces like poverty reduction or economic forces, which are often closely intertwined and are all important to human-cheetah and human-jaguar conflict. However the focus here is on what can be done to manage conflict; for this reason, the networks emphasised the factors that could reasonably be affected by an intervention. Future work could also improve the decision support utility by adding decision nodes and cost information, to more fully support conservation decisions. Finally, it is important to consider that conflict management strategies can only be successful when implemented with a commitment to ongoing evaluation (e.g., [10, 34]). An example of this is the important role of national and international monitoring in the jaguar BN.

Different people have different interests and want different things from conservation policy. Substantial effort is required to bridge these differences [5]. The tools described here can help identify differences in policy objectives. Moreover, given that there are currently insufficient funds available to support the acknowledged, published recovery actions for threatened species, conservation managers and politicians alike are faced with the difficult task of deciding where those limited funds are best used. This process often works first at the policy decision-making level, and then again at the management level, be that within conservation agencies or non-government organizations in receipt of funds. Access to tools such as the BNs and associated products described in this chapter can make it much easier for those charged with making decisions to see where the greatest impact might be gained from particular actions. The tools are also likely to be useful in other areas of natural resource management [26]. Communication, education and participation will be able to be better integrated as a result, something which Jiménez et al. [13] have identified as necessary for improved participation of multiple stakeholders in developing policy and implementing management strategies in biodiversity projects.

We close this discussion with a few concluding comments about the systems approaches that we have proposed in this paper, along with a call for a cautious application of this approach to managing diverse types of data. First, the systems frameworks in general are not suggested as solutions to the whole issue of conservation evaluation and management. Many other statistical and qualitative tools are highly valuable in highlighting particular aspects of these very complex problems. Examples of such tools are population viability analyses, species distribution models, statistical risk models and predictive models based on field data, surveys, focus group meetings and other evaluations.

The second note aims to highlight the simplicity of the integration of information using the proposed approach. The BN framework can accommodate full (conditional) probability distributions where these are available, or alternatively all it requires is discrete (e.g. high-med-low) descriptors. These probability tables can be quantified using a wide range of information, from observational and experimental data, to literature-based estimates, to expert judgement. The exploitation of expert information in these complex problems, based on careful elicitation and probabilistic representation [27], has strong appeal. This use of a simple common currency is similar to economists' use of monetary measures to compare otherwise incommensurable variables.

Thirdly, we note that any quantitative analysis of social or ecological systems (and especially a socio-ecological system) is necessarily a gross simplification of something that is very complex. However, if it was not simplified it could not be done at all. Moreover, despite the simplicity, it is still not trivial to characterise these systems. It is our experience that attempting to do this in a rigorous, transparent manner results in a deeper, if still incomplete, understanding of the system, and is far better than the alternative which is no representation of the system or integration of information at all.

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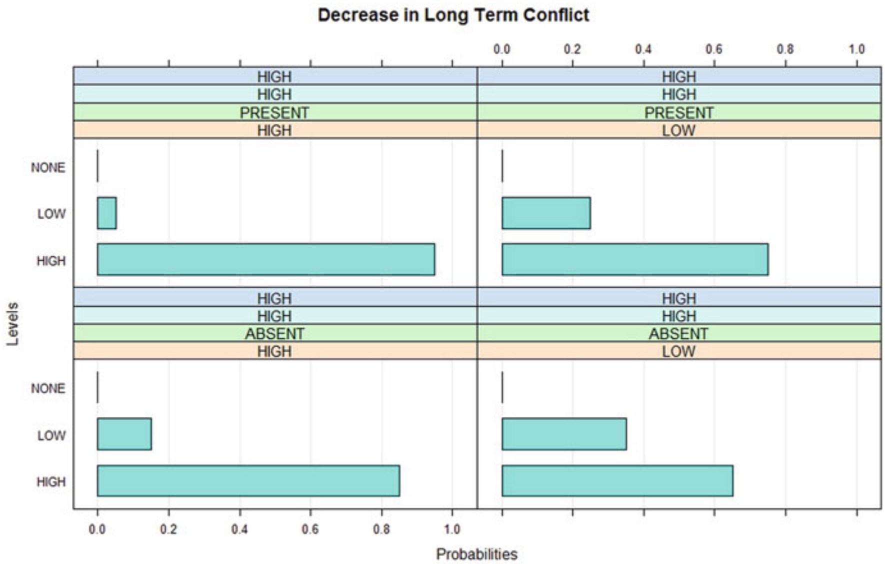
This work is the outcome of two substantive studies undertaken with a range of experts and community members. We thank them all. In particular, for the cheetah study we thank the Mokolodi Nature Reserve for hosting the workshop and Wabotlhe and Brian for reviewing the network, and for the jaguar study we thank the research teams at QUT ACEMS and Vanessa Hunter and Lupunaluz for organising the research trip.

Appendix: Conditional Probability Tables for Long and Short Term Outcomes for Cheetah Case Study

Decrease in Long Term Conflict

Conditional probability tables for decrease in long term conflict with cheetahs in the wild in Botswana, based on the levels of the four parent nodes, respectively Youth Education (violet), Short Term Conflict (light blue), Government Policy (green) and Economic Benefits (orange).


Decrease in Long Term Conflict
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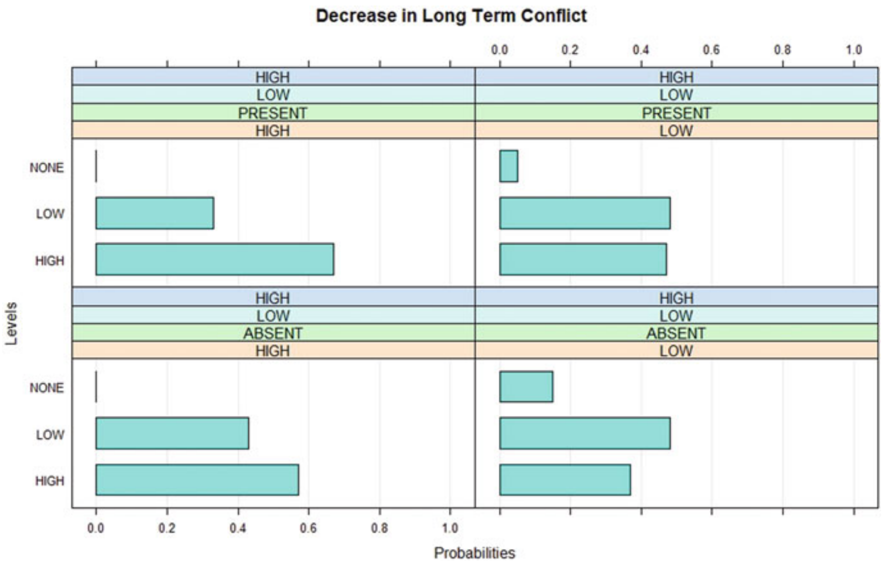
Decrease in Long Term Conflict
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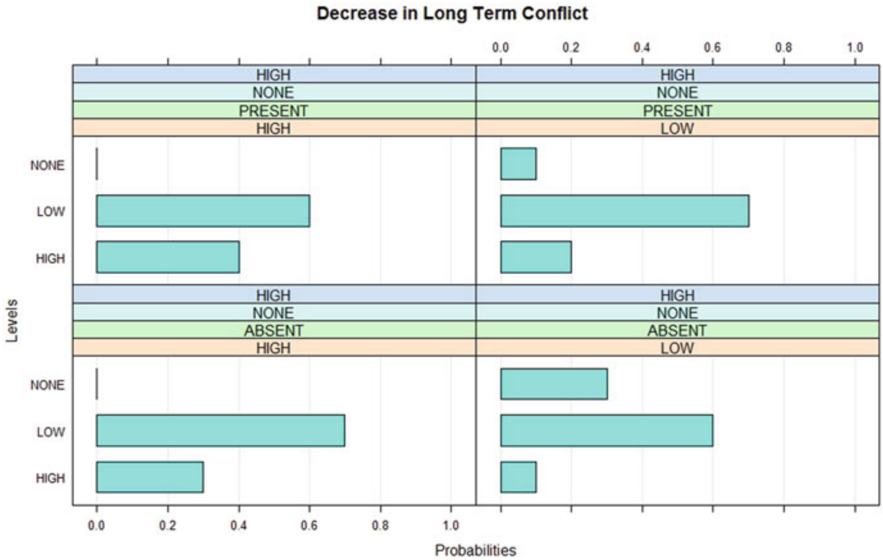
Decrease in Long Term Conflict
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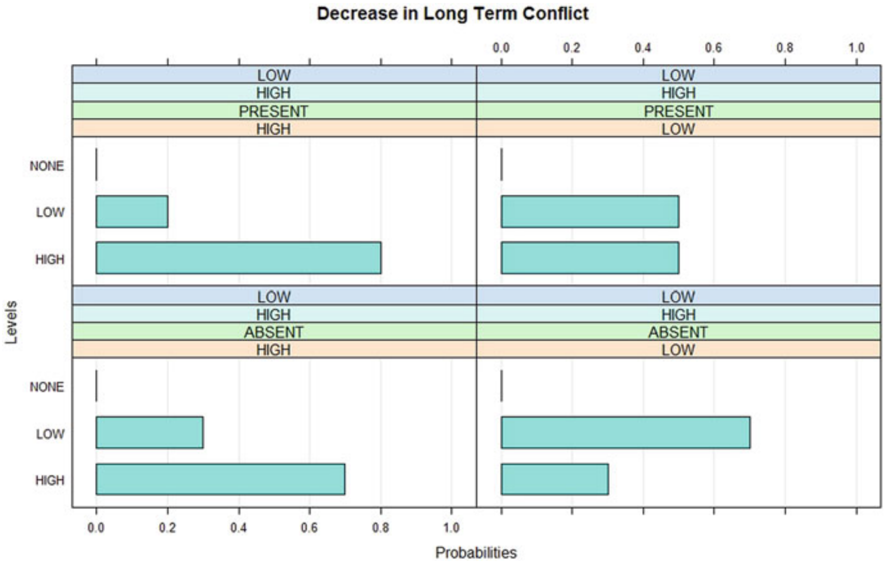
Decrease in Long Term Conflict
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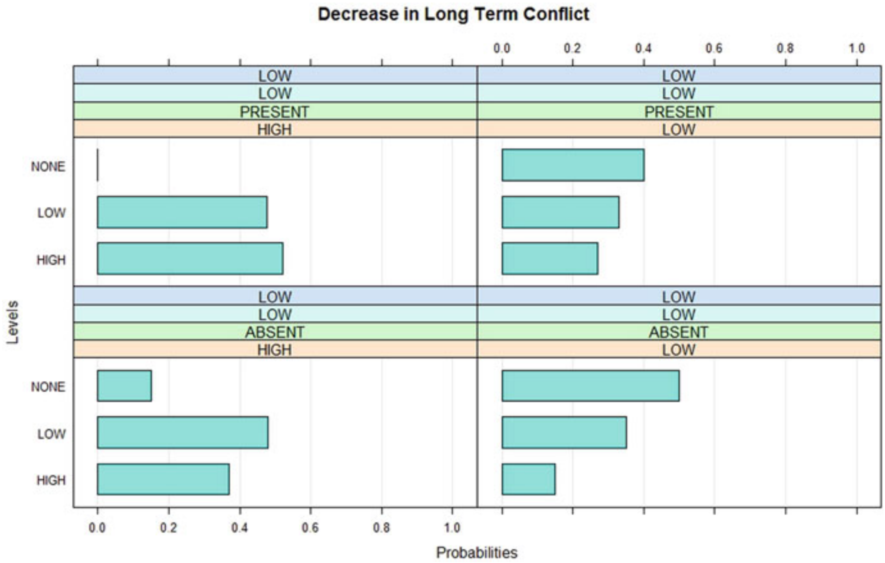
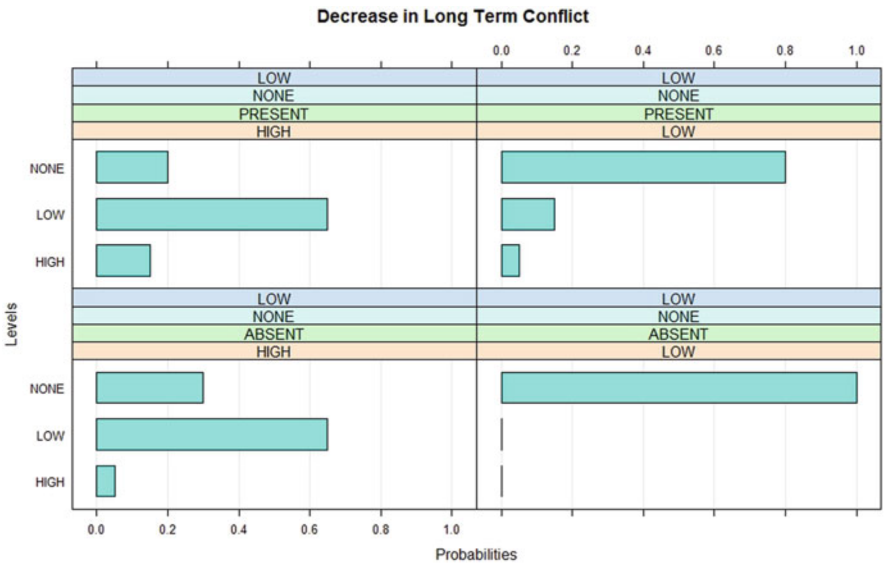
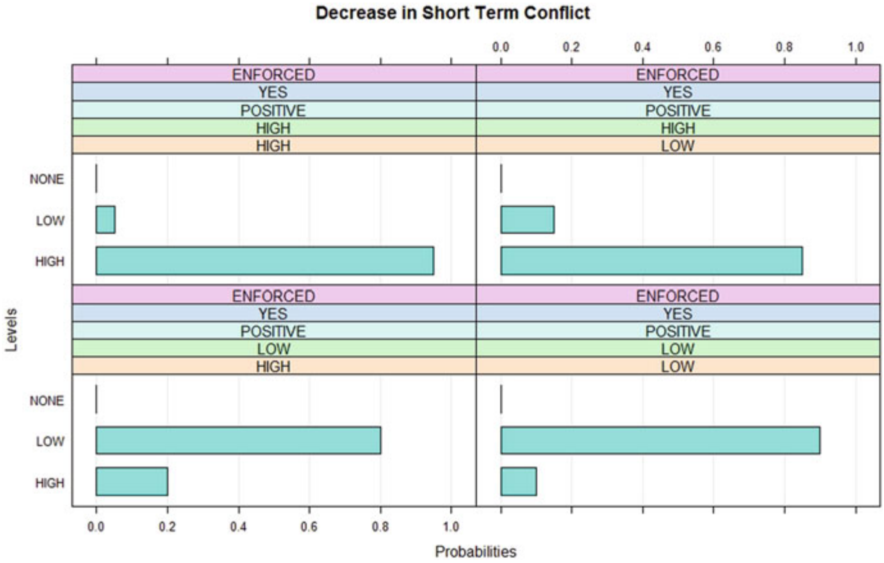




Decrease in Short-Term Conflict

Conditional probability tables for decrease in long term conflict with cheetahs in the wild in Botswana, based on the levels of the four parent nodes, respectively Policy Enforcements (pink), Livestock Protection (violet), Farmer Perceptions (light blue), Economic Benefits (green), Conservation Awareness (orange).


Decrease in Short Term Conflict
ENFORCED
YES
POSITIVE
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ENFORCED
YES
POSITIVE
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HIGH
ENFORCED
YES
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Levels
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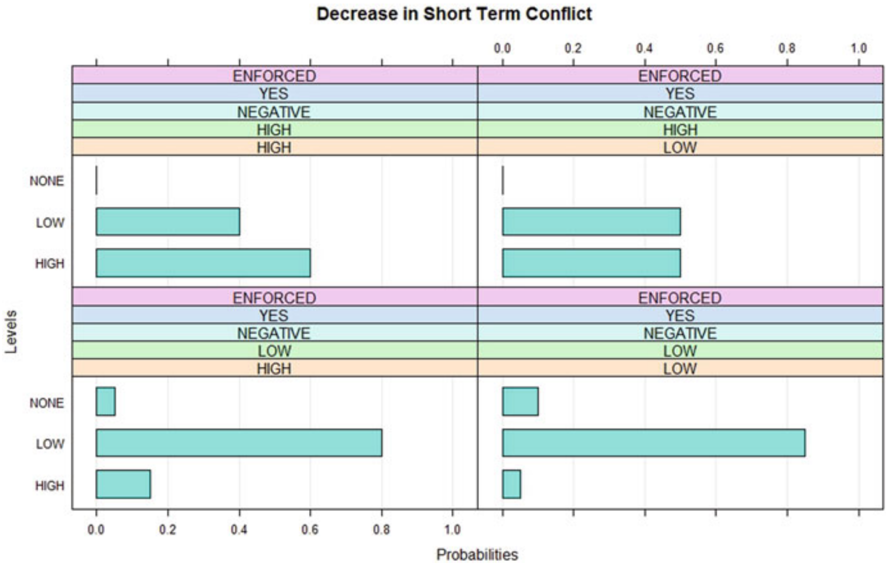
Probabilities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ENFORCED
YES
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ENFORCED
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ENFORCED
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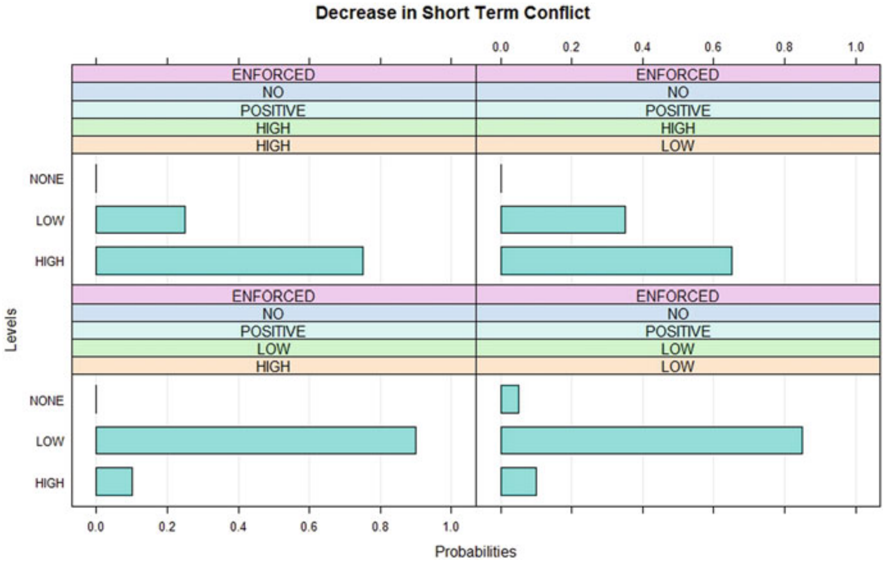
Probabilities


Decrease in Short Term Conflict
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POSITIVE
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ENFORCED
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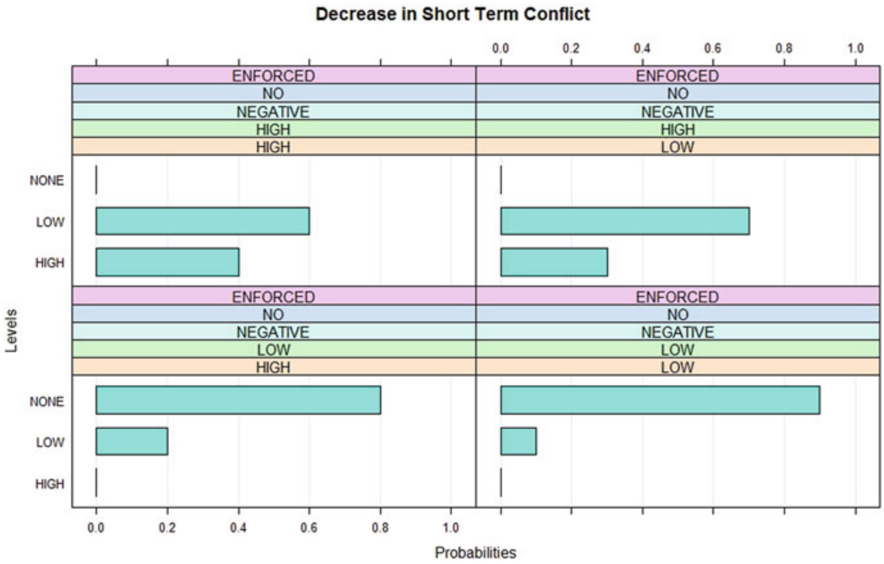
Decrease in Short Term Conflict
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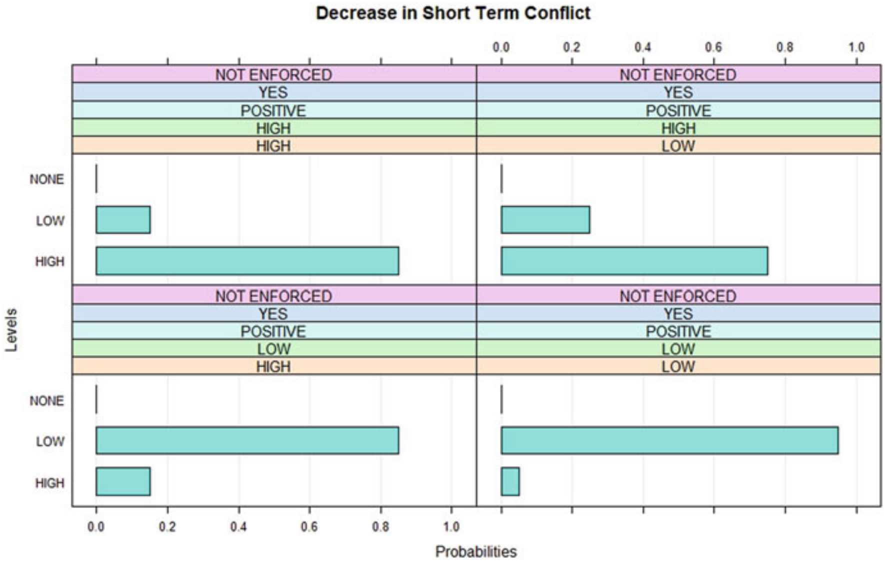
Probabilities


Decrease in Short Term Conflict
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POSITIVE
HIGH
HIGH
NOT ENFORCED
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YES
POSITIVE
LOW
HIGH
NOT ENFORCED
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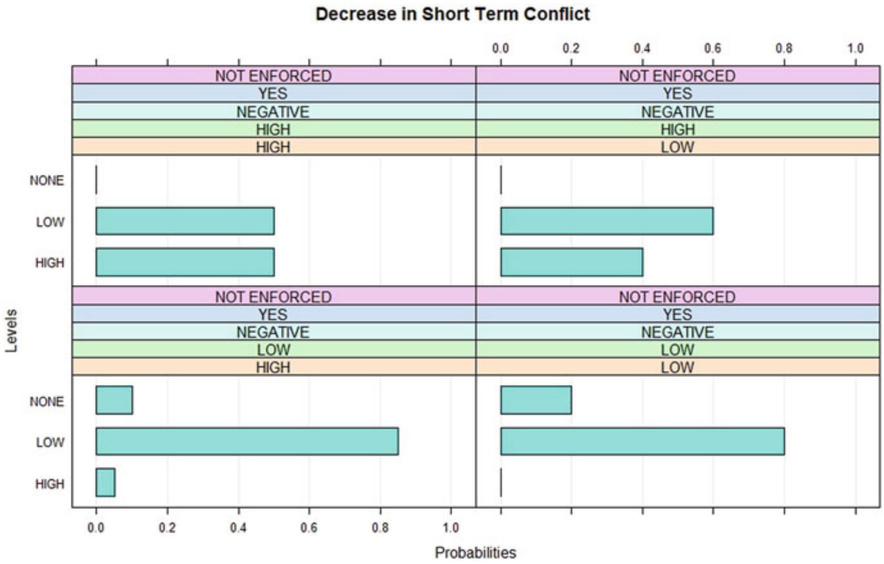
Probabilities


Decrease in Short Term Conflict
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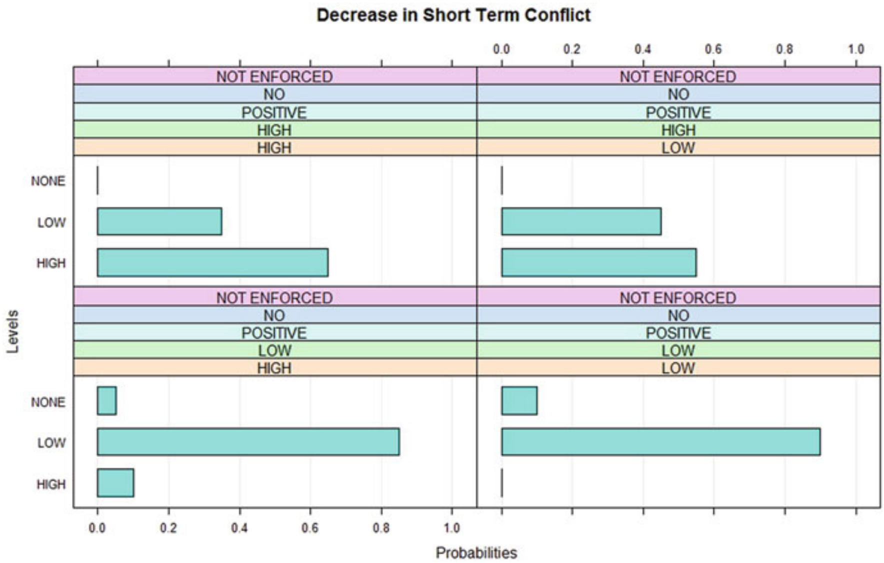

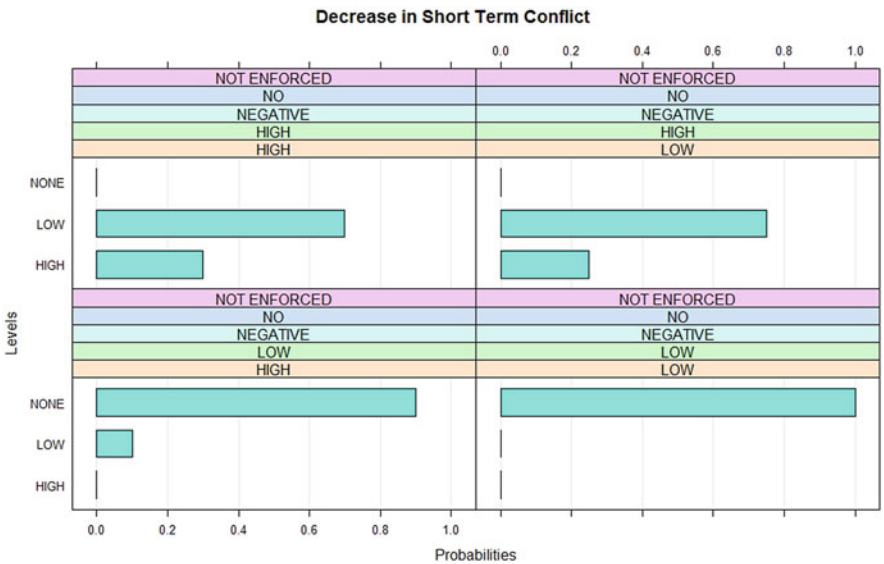

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