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Making a Predictive Diagnostic Model for Rangeland Management by Implementing a State and Transition Model Within a Bayesian Belief Network (Case Study: Ghom- Iran)

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1. Introduction

Rangelands are landscapes in which the native vegetation (climax or natural potential) is predominantly grasses, grass-like plants, forbs, or shrubs. They are defined as land where vegetation management is accomplished mainly through the manipulation of grazing and include land that is re-vegetated naturally or artificially (SRM, 1989). The world's rangelands are grazed because they do not have the capacity to be cultivated. They are globally significant semi-natural landscapes that have been used for many purposes including grazing, apiculture, hunting, mining and tourism. The degradation of rangelands, which cover more than 47 % of the globe (332 million hectares) (Tueller, 1988), has been reported in all parts of the world. For instance, more than 70% of rangelands in Africa, Asia and America and about 54% in Australia are to some degree degraded. Better understanding of the ecological processes in rangelands and of the products they provide are required to effectively maintain and manage this valuable resource.

Rangelands are highly complex adaptive socio-ecological systems with complicated interactions between the rangelands, livestock and humans (Gross et al., 2003; Gross et al., 2006). Leohle (2004) categorised the sources of ecological complexity, which are notable in rangelands, into six groups: spatial, temporal, structural, process, behavioural and geometric. Interactions between these components in a broad range of spatial and temporal scales are among the main reasons for their complexity. A lack of understanding in any part leads to an inability to identify the best policies and strategies for management (Walker & Janseen, 2002). Misunderstanding of these interactions by humans is responsible for a worldwide deterioration in rangeland ecosystems. The inherent complexity of ecological parameters and uncertain social and economic effects significantly adds to the difficulties of developing a sound understanding of rangelands. In addition, there may also be conflicts in the multiple objectives of rangeland use and management (e.g. production and conservation). Anti-degradation programs fail if they do not consider the interactions between the ecological, social and economic parameters within rangeland ecosystems.

The lack of availability of scientific knowledge (research results and experiences) at the time of decision-making by the different stakeholders and policy makers is one of the reasons for the failure of rangeland management programs. This knowledge is scattered over a wide range of resources and is not easily accessible even for scientists. In addition, the lack of integrating scientific knowledge, with landholders' knowledge and the slow response to the uptake of new knowledge by land managers hinders the success of management programs (Bosch et al., 2003).

It could be argued that most knowledge is available, but the formats in which rangeland managers would require such knowledge is often not accessible in an appropriate form. Translation of knowledge into practical applications is a prerequisite if this knowledge is to be used in management programs (Provenza, 1991).

1.1 Decision support tools in range management

Many simulation models have been developed by researchers for the purpose of predicting the outcomes of rangeland management decisions. These models help to:

- Organise and structure different sources of knowledge about rangeland systems;
- Identify and focus on the knowledge gaps;
- Promote a multidisciplinary approach to rangeland management;
- Provide an efficient means of capturing the complex dynamics of rangeland systems (Carlson et al., 1993).

There are many Decision Support Tools (DSTs) relevant to rangeland management that are based on simulation models (Carlson et al., 1993). Some of these DSTs have been specified for a single purpose or are appropriate for limited objectives or areas of application, while some have wider application. However, most models have been developed as research tools which require large data inputs. A good understanding of data requirements is needed for all models to assess their application and to evaluate their appropriateness and output value (National Land & Water Audit, 2004). This makes them inaccessible to most land managers.

An additional difficulty is the fact that uncertainty in the prediction of management outcomes is not accommodated in these DSTs. Uncertainty exists when there is more than one outcome, consistent with the expectations (Pielke, 2001, 2003). Decision-makers are interested in quantifying and reducing uncertainty. The degree of confidence in model predictions is therefore an important aspect to be included in the design of useful DSTs. Finally, it is the decision-makers task to understand and use the DSTs. It is therefore important that they are involved in developing the tools. Using the end-users' experiential knowledge could play a vital role in ensuring credibility and increasing the adoption of a DST.

1.2 Adaptive management

Adaptive management has become an important approach to cope with uncertainty, imperfect knowledge and complex systems. In this approach, outcomes of management are continuously used to modify or adapt management (Sabine et al., 2004; Morghan et al., 2006). This is particularly important for rangelands where the outcomes of management are often unknown or difficult to predict. Adaptive management "structures a system in which monitoring iteratively improves the knowledge base and helps refine management plans" (Ringold et al., 1996, P.745). However, a framework is needed that allows for this knowledge to be updated and ensures its accessibility for future decision-making. Such a framework must be able to predict the probable outcomes of rangeland management decisions based on the existing knowledge of vegetation dynamics. Such a framework should also accommodate the uncertainty associated with these predictions.

1.3 Framework for adaptive management

The State and Transition Model (STM) provides a simple framework for integrating knowledge about vegetation dynamics and the possible responses of vegetation to management actions and environmental events. Both qualitative and quantitative knowledge could be accommodated in an STM, and it has the potential for organising and updating new knowledge that becomes available through monitoring (Vayssieres & Plant, 1998). The STM is also ideal for improving communication between rangeland scientists, end users and policy makers. Using this model as a framework enables landholders to focus on opportunities (e.g. transition to productive states) and avoid hazards (e.g. transitions to degraded states where the reverse transitions are problematical since they will be too costly to reverse or not be practical in a normal management time scale) (Westoby et al., 1989; Brisk et al., 2005).

Many scientists have used these concepts for developing STMs for various rangelands following their introduction by Westoby et al. (1989), who introduced this model based on non-equilibrium ecology (Friedel, 1991; Laycock, 1991; Hall et al., 1994; Allen-Diaz & Bartolome, 1998; Phelps & Bosch, 2002; Knapp et al. 2011). Typically most of the STMs presented so far are simple flowcharts with a catalogue of states and transitions. These models are traditionally descriptive and are unable to be used as predictive models. Also, most of the models produced so far are characterised by a lack of practical application and simply provide "proof- of concept examples" (Vayssieres & Plant, 1998). However, they handle poorly the uncertainty associated with cause and effect.

Bayesian Belief Networks (BBNs) (Jensen, 1996) provide a tool that can help solve this problem. They allow for the construction of cause and effect models, and relate variables using conditional probabilities. This allows for uncertainty to be explicitly incorporated into models. BBNs can also be used to perform sensitivity and scenario analysis, allowing managers to predict the probable outcomes of management actions or identify those management actions that are most likely lead to desirable outcomes. An added benefit of BBNs is that they can be easily updated using the results of monitoring. These monitoring results can be used to update the probability relationships over time, allowing the outcomes of previously implemented management decisions to modify model predictions. Therefore, BBNs provide a mechanism for supporting adaptive management.

This chapter aimed to demonstrate how a STM can be converted into a user-friendly management decision support tool. This includes several steps including (a) converting the State and Transition diagram into a BBN influence diagram, (b) determining probabilities for the BBN model through literature studies and the knowledge of scientists that are familiar with the vegetation dynamics of the study area and finally (c) testing model behaviour by sensitivity and scenario analysis. A STM for the Steppe zone of Qom- Iran was used as an example to demonstrate the process.

2. Case study in Iran

2.1 Study area

The study area is located in Ghom rangelands, 130 km from Tehran, the capital city of the Islamic Republic of Iran. This area is surrounded by central Iranian desert and has an arid climate. The Steppe zone of Ghom has an annual rainfall of between 100 to 230 mm, which is highly variable both within and between seasons. Most precipitation occurs in winter with the dry season occurring for 4 to 6 months over summer. A significant portion of the limited precipitation is lost as run-off and then evaporation.

The vegetation in the Steppe zone of Ghom is sparse with evenly distributed individual dwarf shrubs and/or bunchgrasses. The perennial cover can vary from 1 to 35%, while the spaces between perennials remain bare or briefly covered by Therophytes after rainfall events. The most common life-form is shrubby species (browse species) and subshrubs (dwarf shrubs). The contribution of the subshrubs is about 40% of the perennial species, while about 30% of those are shrubby species. The most frequently occurring species is *Artemisia sieberi*. Woody plants that grow with *Artemisia sierberi* are *Dendrostellera lessertii*, *Ephedra sp*, *Astragalus sp*, *Achillea sp*, *scariola orientalis*, *Acantholimon sp*, *Acanthophylum sp*, and *Stachys inflate*. *Stipa hohenackeriana* is the most abundant perennial grass but it has disappeared from some areas. *Stipagrostis plumose* is another dominant perennial grass, however, is only found on light soils and never on heavy or saline soils

The Bureau of Rangelands has developed several strategies to enhance rangeland condition, including de-stocking, water harvesting and transplanting of palatable shrubs. The challenge is when and where to implement these strategies to obtain the best result. The effect of these strategies on the dynamics of the vegetation is also uncertain. The unavailability of an appropriate DST hinders the selection of appropriate management strategies.

2.2 Creating a State and Transition Model (STM)

The iterative model development process was used to construct an STM for the Steppe zone of Ghom Iran. This process utilised multiple information sources to identify possible vegetation states and transitions.

There were no published STMs for this area, so the process utilised multiple information sources to identify possible vegetation states and transitions. First, the limited literature available was used to draft a catalogue of states and transitions. Then it was refined through discussion with scientists familiar with the vegetation dynamics of the Ghom area. Vegetation states were defined using vegetation composition and soil erosion status. The favourability of each state was explained from an animal productivity and soil stability point of view.

Figure 1 shows the STM developed for the Steppe zone of Ghom. The STM consists of 7 vegetation states and 15 transitions (see Table 1 & Table 2).

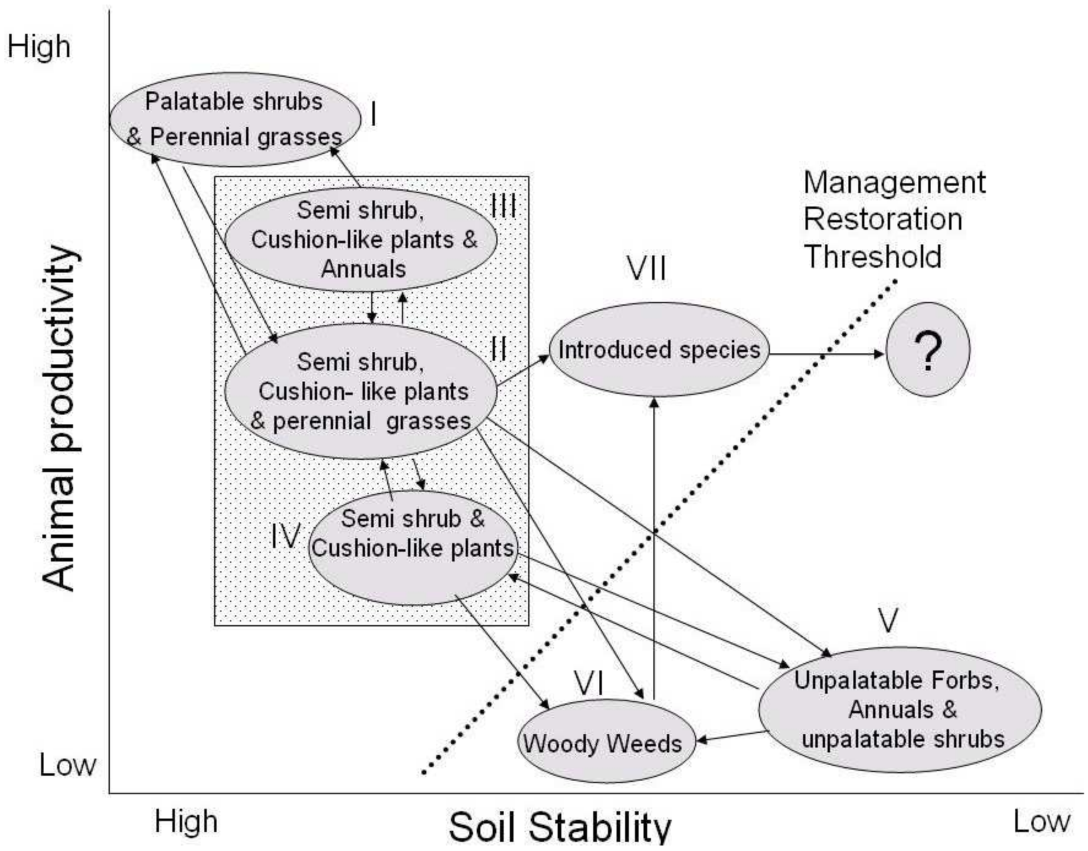

Fig. 1. STM for Steppe zone of Ghom, Iran based on the experiential knowledge of Iranian researchers.

Number of states	State of vegetation	Species Composition	Maximum frequency (%)	Some Ecological Information
I	Palatable shrubs & perennial grasses	*Artemisia sieberi*	15	This state has a high grazing value and generally has high litter, and projected cover of 30%. Pasture yield in this state is high; erosion level is low because it is dominated by shrubs and perennial grasses; thus, soil stability is high.
		Buffunia mucrocarpa	10	
		Pteropyron sp	5	
		Salsola tomentosa	5	
		Andrachne sp	5	
		Ajuga sp	5	
		Kochia sp	5	
		Stipa hohenackeriana	20	
		Other	30	
II	Semi shrub, cushion-like plants & perennial grasses	*Artemisia sieberi*	60	Erosion is low to moderate. This state represents the overall condition in the Steppe zone.
		Cushion-like plants	10	
		Stipa hohenackeriana	5	
		Other	25	

Table 1. Continued

Number of states	State of vegetation	Species Composition	Maximum frequency (%)	Some Ecological Information
III	Semi-shrub, cushion-like plants and annuals	*Artemisia sieberi* Cushion-like plants *Stipa hohenackeriana* Annuals	60 10 5 25	Its composition is the same as state II, but is highly preferred by sheep and goats due to abundant foliage of annuals. It can have up to 30% cover of annual grasses and forbs.
IV	Semi-shrub & cushion-like plants	*Artemisia sieberi* Cushion-like plants *Noaea mucronata* *Stipa hohenackeriana* Others	50 30 5 1 14	In this state, palatable shrubs such as *Salsola tomentosa* have disappeared and frequency of tall grass species such as *Stipa hohenackeriana* decreases dramatically. Erosion is high.
V	Unpalatable forbs, annuals and unpalatable shrubs	*Peganum harmala* *Launaea acanthodes* *Euphorbia spp* Cushion-like plants *Artemisia sieberi* *Noaea mucronata* *Scariola orientalis* Annual grass Annual forbs Other	5 5 5 5 20 10 10 5 5 30	This represents the most degraded state, there are no perennial grasses in this state and also *Artemisia sieberi* has a low frequency. The percentage cover is less than 10% and erosion is high.
VI	Woody weeds	*Reseda sp* *Hulthemia persica*	10 90	Some species (*Reseda sp* and *Hulthemia persica)* have infested these areas that were formerly cultivated. A highly stable state with lowest value for grazing.
VII	Introduced species	*Atriplex spp* *Artemisia sieberi* Cushion-like plants *Stipa hohenackeriana* Others	50 20 10 5 15	This state has two stratifications. *Atriplex spp* constitutes the upper while various other species are located in the lower level of the vegetation structure. The total percentage cover is low and the frequency of species such as *Artemisia sieberi* declines to the that of state V.

Table 1. Catalogue of vegetation states for Steppe zone of Ghom.

Transition number & name		Main causes	Probability	Time frame (years)
1	I, II	Grazing pressure (Moderate), Selective grazing (High), Early grazing	High	5-10
2	II, I	Destock, Wet season in time period (Frequent), Seed and plant of palatable shrub available	High	>10
3	II, III	Wet season in time period (Frequent)	High	1-2
4	II, IV	Grazing pressure (High), Drought, Soil compaction (High)	High	3-10
5	II, V	Grazing pressure (Very high), Drought (Frequent), Soil compaction (High)	High	5-20
6	II, VI	Ploughing	High	2-5
7	II, VII	Transplanting Seedling of *Atriplex spp*, Wet season in time period (Frequent),Irrigation of seedlings in initial years	High	3-5
8	III, I	Destock, Wet season in time period (Frequent), Seed and plant sources	Moderate	>10
9	III, II	Wet season in time period (Infrequent)	High	1-2
10	IV, II	Grazing pressure (low), Wet season in time period (Frequent), Seeds and plant sources decrease	High	5-10
11	IV, V	Grazing pressure (High), Drought (Frequent), Soil compaction (High)	High	5-10
12	IV, VI	Ploughing	High	2-5
13	V, IV	Grazing pressure (low), Wet season in time period (Frequent), Seed and plant sources	Low to moderate	2-5
14	V, VI	Ploughing	High	2-5
15	VI, VII	Erasing Woody weeds, Plantation of *Atriplex spp*, Wet season in time period (Frequent)	Moderate	3-5

Table 2. Catalogue of transitions for the Steppe zone of Ghom.

2.3 Creating a BBN for modelling vegetation change

Figure 2 outlines the main steps used in this study to build a DST for rangeland management. The STM for Stepp zone of Ghom (outlined above) was the starting point for model development. From the STM, an influence diagram was built to show the possible transitions and the factors influencing each transition. Next, the influence diagram was populated with probabilities to produce a predictive model, and finally the behaviour of the model was tested using scenario and sensitivity analysis.

2.4 Building an influence diagram

An influence diagram is simply the graphical component of a BBN. From the STM, an influence diagram was constructed to show the possible transitions and the factors influencing each. The framework contains a node representing possible starting vegetation states, nodes representing possible transitions from each of these states to other states, nodes representing the main factors influencing these transitions and their sub-factors , and time frame of possible changes.

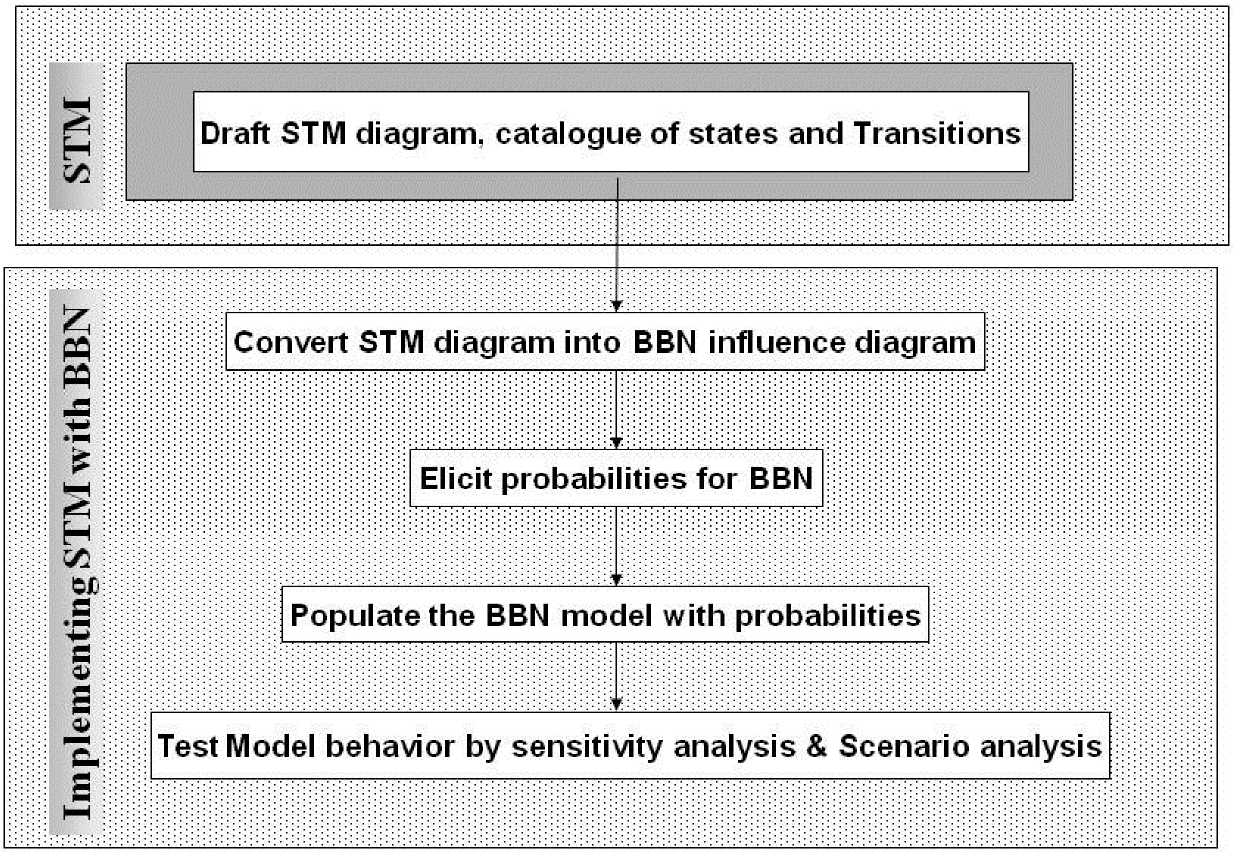

Fig. 2. Steps used to build a decision support tool.

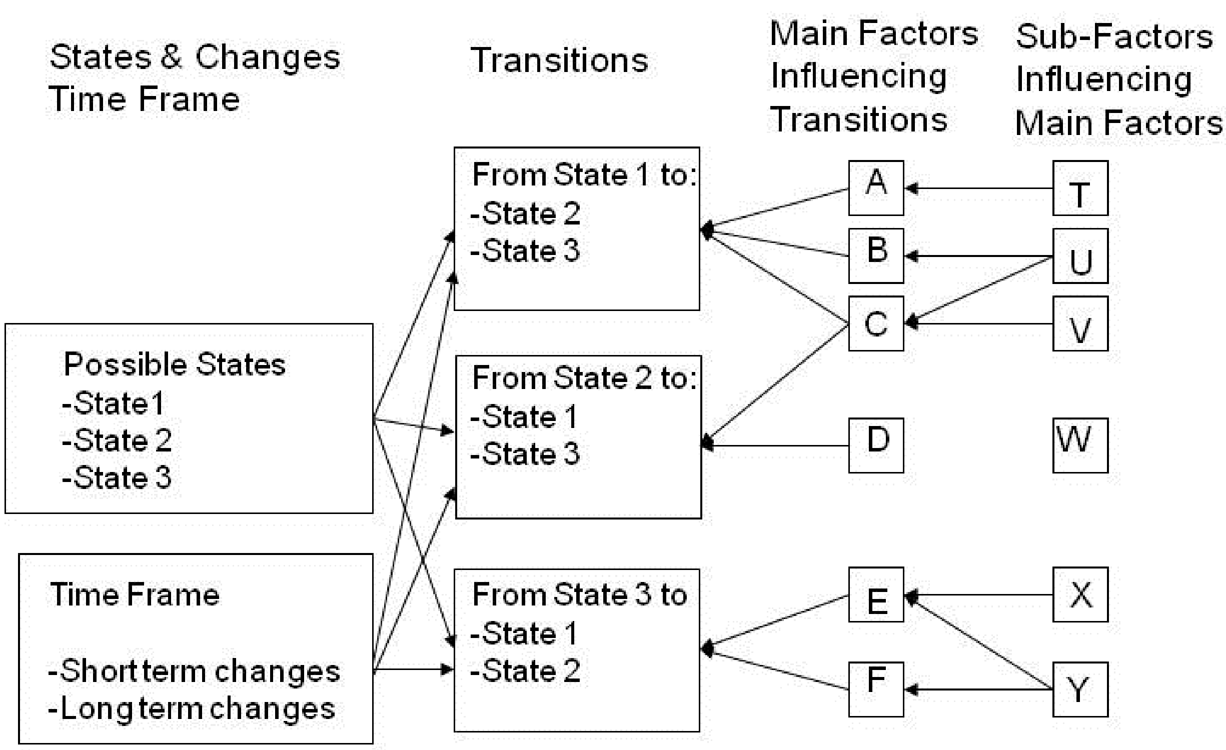

Fig. 3. This framework was used to construct Bayesian network structure from an STM (adapted from Bashari et al., 2009).

Next, states were defined for each node in the influence diagram. For the transition nodes, their states were the vegetation states in the STM. For the remaining nodes, that is the main factor and subfactor nodes, states were defined in consultation with the rangeland scientists who participated in building the STM. Figure 4 shows the completed influence diagram for the Steppe zone of Ghom and table 3 lists the states and the definitions for each node in the influence diagram.

Monitoring data or simulation models were not available to populate the influence diagram with conditional probabilities, so subjective probability estimates were obtained from the rangeland scientists who participated in building the STM.

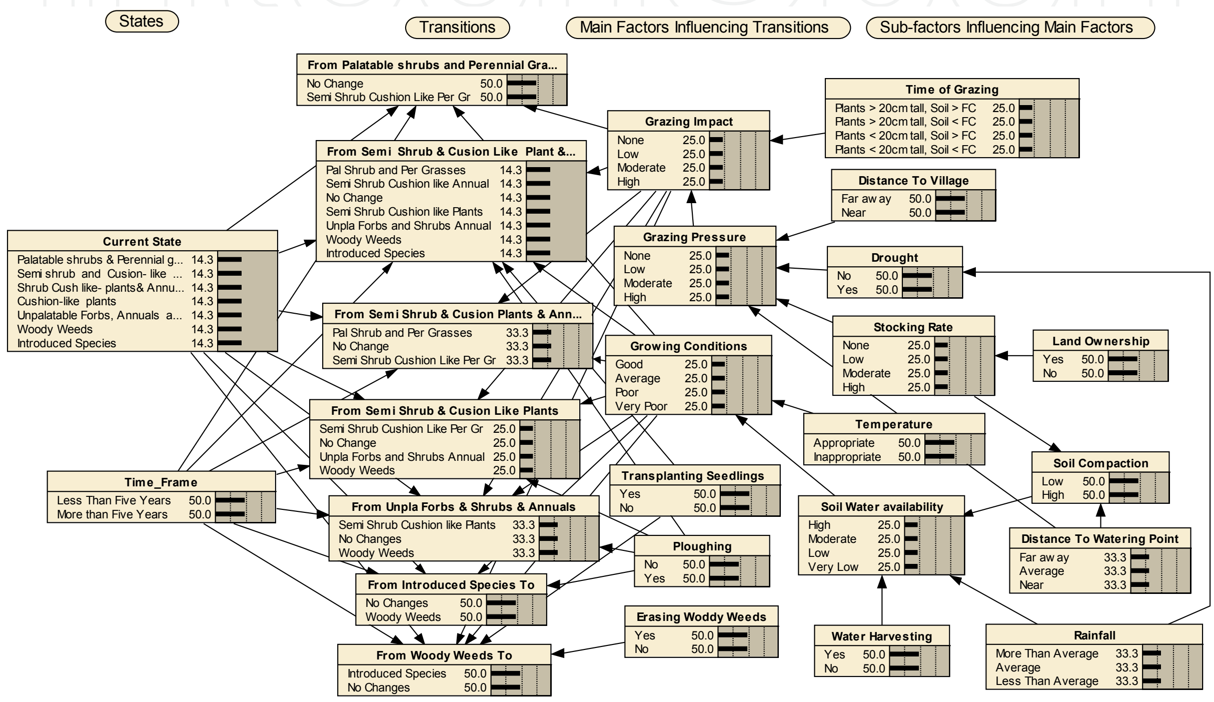

Fig. 4. Influence diagram of vegetation change for the Steppe zone of Ghom. Pal = Palatable, Per = Perennial, Unpla= Unpalatable, Gr = Grass, An = Annual

Node	States	Definition
Current State	PSPG	Palatable shrubs & Perennial grasses (PSPG), Including high frequency of 3P grasses (Productive, Palatable, Perennial) and palatable shrubs such as *Salsola tomentosa* and *Andrachne sp*, it has highest production and stability;
	SSCPPG	Semi-shrub and Cushion-like plants & Perennial grasses (SSCPPG). This state represents the overall condition in the Steppe zones and contains *Artemisia Sieberi* and *Stipa hohenackeriana* and some Cushion-like plants as dominant species;
	SCPA	Shrub, Cushion-like plants and Annuals (SCPA). Its composition is the same as SSCPPG but this state is highly preferred by sheep and goats due to of the abundant foliage of annuals. It is estimated this state can have up to 30% cover of annual grasses and forbs;
	SSCP	Semi-shrub & Cushion-like plants (SSCP). In this state, palatable shrubs such as *Salsola tomentosa* have disappeared and frequency of tall grass species (e.g. *Stipa hohenackeriana*) decreases dramatically. Erosion is high;
	UFAUS	Unpalatable forbs, Annuals and Unpalatable shrubs (UFAUS). This state represents the most degraded state. There are no perennial grasses and *Artmisia sieberi* has low frequency. The percentage cover is less than 10% and erosion is high;

Table 3. Continued

Node	States	Definition
	WW;	Woody Weeds (WW). Although it is a highly stable state; its species are not edible by livestock. In the early years after ploughing, the frequency of *Reseda sp* is higher but later on *Hulthemia persica*, a native weed of the Steppe zone, becomes dominant;
	IS	Introduced Species (IS). This state has two levels in which *Atriplex spp* constitutes the upper level, while various other species form the lower level of the vegetation structure. The percentage cover is low and the frequency of species such as *Artemisia sieberi* declines.
Time Frame	< five years > five years	Represent the likely years of transition under defined scenarios, Less than five years represents transitions occurring over short periods and more than five years represent transitions over longer periods of times (E.g. up to 10 or 20 years).
From PSPG to	No changes SSCPPG	The same as current state definition
From SSCPPG to	PSPG SCPA No change SSCP UFAUS WW IS	The same as current state definition
From SCPA to	PSPG No change SSCPPG	The same as current state definition
From SSCP	SSCPPG No change UFAUS WW	The same as current state definition
From UFAUS to	SSCP IS No change WW	The same as current state definition
From WW to	IS No change	The same as current state definition
From IS to	No change WW	The same as current state definition
Grazing Impact	None	None : when destocked
	Low	Low : when grazing pressure is low and grazing is during a time of range readiness
	Moderate	Moderate : when the plant is affected by grazing but the grazing pressure is in line with the carrying capacity and the appropriate time of grazing; if the grazing occurs when the range is not in a stage of readiness, even the low grazing pressure can have a moderate grazing impact
	High	High : when the grazing pressure is high and the grazing occurs when the range is not in a stage of readiness
Early Grazing	No Yes	Grazing rangeland prior to range readiness (e.g. grazing before grass plants reach the third leaf stage or grazing when soil is not dry enough to prevent damage to soil structure and plants)

Table 3. Continued

Node	States	Definition
Grazing pressure	None Low Moderate High	Represents the balance between how much the animals eat and how fast the pasture is growing. Grazing pressure (GP) = rate of removal of pasture / rate of supply of pasture. GP=0 None; GP<1, Low GP=1, Moderate, GP>1, High
Growing condition	Good Average Poor Very poor	Good : when Soil Water Availability (SWA) is sufficient for plant growth and the temperature is appropriate Average : when the SWA is average and temperature does not produce a major limitation for plant growth Poor : when the SWA is low or temperature causes some limitation for plant growth Very Poor :when SWA is very low and/or temperature causes a major limitation for plant growth
Soil water availabi-lity	Hi Average Low Very Low	Amounts of soil moisture (SM) available to support plant growth; High = when the soil water content is above the wilting point for most of the growing season Average: SM is available for 50 to 70% of the growing season Low : SM is available for 20 to 50%of the growing season Very Low : SM is available for less than 20% of the growing season
Transplan-ting Seedling	Yes No	Refers to whether seedlings of shrub species such as *Atriplex spp* are transplanted or not
Ploughing	No Yes	Refers to whether a site is ploughed or expansion of rainfed agriculture or not
Erasing Woody weeds	Yes No	Refers to use of appropriate mechanical or chemical treatment to control and eradicate woody weeds
Stocking rate	De-stocked Low Moderate High	It describes how many animals a site can support. Destocked : using enclosures to keep the livestock out of a site Low : the animal consumption is less than the available forage Moderate : the animal consumption and available forage is equal High : the animal consumption is more than the available forage.
Distance to Village	Far away Near	Refers to the distance of the rangeland to the village, the closer the rangeland is to the village, the more likely it will be grazed by livestock
Drought	No Yes	Severe rainfall deficiencies over a year (there is a significant effect on vegetation when the rainfall is below 75% of the long term mean)
Soil Compac-tion	Low High	Refers to the severity of soil compression. Low : good soil structure, only slight evidence of hard pans or surface crust. High : poor soil structure, evidence of hard pans and surface crust
Distance to watering point	Far away Average Near	Accessible area around watering points grazed heavily. Far away : >5 km away Average : 1km to 5 km, Near: < 1km
Water Harves-ting	Yes No	Determines whether water harvesting techniques such as contour furrow or pitting are used or not
Rainfall	High Average Low	High : > 150mm in areas at 1000 m above sea level and >200 mm in areas above 1300 m Average : 150mm at 1000 m & 180mm at above 1300m Low : <150 at 1000m & <180mm at above 1300 m
Tempera-ture	Appro-priate Inappro priate	Explains the temperature conditions that affect the phenological status of plants; Appropriate: no unseasonal temperatures occur; Inappropriate : unseasonal temperatures occur and cause some damage to new growth.
Land ownership	Yes No	Explains the land tenure status: Yes:privately owned and used No : publicly used

Table 3. State definitions for nodes in the Steppe zone influence diagram (Fig. 4).

2.5 Making sense of the BBN model

Finally, the behaviour of the model was tested using scenario and sensitivity analysis. The results of the sensitivity analysis were returned to the Iranian rangeland scientists for review and feedback. If the scientists disagreed with the behaviour of the model, the conditional probability tables were revisited.

The sensitivity analysis revealed that grazing impact and growing condition were the two most important drivers of almost all transitions except for two (Table 4). "Grazing impact" represents the management influence on transitions and "growth condition" represents the environmental influence on transitions. These two had similar influences on most transitions. This result is supported by other studies in Iran, which suggest that frequent droughts coupled with mismanagement (e.g. overgrazing) combine to produce rapid land degradation (Nemati, 1986; Badripour, 2005). However, this result does not match the beliefs of governors or livestock managers. Most governors believe that grazing is the dominant factor responsible for rangeland degradation, while livestock managers believe that it is drought and growing conditions.

Drought and time of grazing had an effect on many transitions but only through their affect on grazing impact. High grazing impact allows the establishment of undesirable shrub species such as *Scariola orientalis* and *Noaea mucronata,* which compete heavily with favourable species for limited resources, especially water. Over-utilization with prolonged drought can reduce the tussock size of desirable perennial grasses, increasing the risk that they will be permanently lost from the rangeland seed bank. Unseasonal temperatures and low soil water availability increased the likelihood of poor or very poor growing conditions, making transitions to unpalatable forbs and annual states more likely.

The Steppe zone soil is generally low in organic matter. As a consequence, aggregate stability is low and the risk of soil compaction, surface sealing, and crust formation is high when overgrazing occurs, especially on silty soils. Hence, it is combination of poor soil characteristics and overgrazing that can lead to reduced rainfall effectiveness and soil water availability, triggering transitions to degraded states (Whisenant, 1999). In this case, water harvesting techniques are often needed to improve soil water availability and bring about transitions to palatable shrubs and perennial grasses.

The planting of seedlings was important in avoiding transition to introduced species states. The establishment of sown shrubs can also benefit from water harvesting techniques (Schreiber & Frasier, 1978). Nemati (1986) found water harvesting treatments for 5 years led to the recovery of *Artemisia sieberi*, *Stipa hohenackeriana*, *Aristida plumosa* , *Salsola spp*., and *Astragalus siliquosus* in the Steppe zone. Irregular precipitation is the main reason for poor natural recruitment in rangelands and the establishment of sown rangelands in the Steppe zone (Monsen, 2002). It is therefore advisable to raise seedlings in a nursery and to transplant them prior to seasonal rains. Overgrazing, untimely grazing, drought and unseasonable temperatures can kill newly planted seedlings and thereby cause undesirable transitions.

Ploughing was an important driver of transitions to a state of woody weeds. Ploughing is a common cause for the establishment of woody weeds, such as *Reseda sp* and *Hulthemia persica*, in the Steppe zone. Ploughing often occurs near villages, not for cultivation or the expansion of rainfed agriculture, but to claim land ownership. Transitions away from woody weed are very expensive and require weed control plus the sowing of improved rangeland species such as *Atriplex spp* and *Eurotia ceratoides*. Spelling of rangeland is also required to allow sown rangelands to establish.

2.6 The modelling approach

BBN models have the ability to provide rangeland managers with decision support through their analytic capabilities. As mentioned before, two main types of analysis can be performed using a BBN, (a) prediction, and (b) diagnosis. Predictive analysis can be used to answer "what if" questions and diagnostic analysis can be used to answer "how" questions.

Figure 5 is an example of the Steppe zone of Ghom BBN used for predictions. Here, the selected states of input nodes (outer boxes) represent a scenario for a site. In Figure 5, the site is currently in the "Palatable shrubs and perennial grasses" state and the model is being used to predict the chance of a transition away from this state within a more than five years timeframe (note that the state "More than five years" is selected in the "Timeframe" node). The model shows that, under the selected scenario, the chance of transition away from "Palatable shrubs and perennial grasses" to "Semi shrub and cushion like plant" is relatively high (60.9%). The model also indicates the probable causes for this transition, that is, the probable high grazing impact (91.3%) and poor growing condition (62.4%). These causes were also highlighted by sensitivity analysis using the model (Table 4), which showed that the transition from "Palatable shrubs and perennial grasses" to "Semi shrub and cushion like plant" was most sensitive to grazing impact and growing condition. Table 5 shows the full conditional probability table "From palatable shrubs & perennial grasses" state.

Transition Number	Transition Name	Grazing impact	Growing condition	Ploughing	Transplanting seedlings	Erasing weeds
1	I, II			*	*	*
2	II, I					*
3	II, III			*	*	*
4	II, IV			*	*	*
5	II, V			*	*	*
6	II, VI				*	*
7	II, VII			*		*
8	III, I			*	*	*
9	III, II			*	*	*
10	IV, II			*	*	*
11	IV, V			*	*	*
12	IV, VI				*	*
13	V, IV			*	*	*
14	V, VI				*	*
15	VI, VII			*		

				*
High influential	Moderate influential	Low influential	Very Low influential	None influential

An asterix (*) means that this factor had no influence on the transition.

Table 4. Summary of sensitivity analysis performed on the transition nodes in the Steppe BBN. The shading indicates the relative influence of factors on each transition, from most influential (black) to least influential (white).

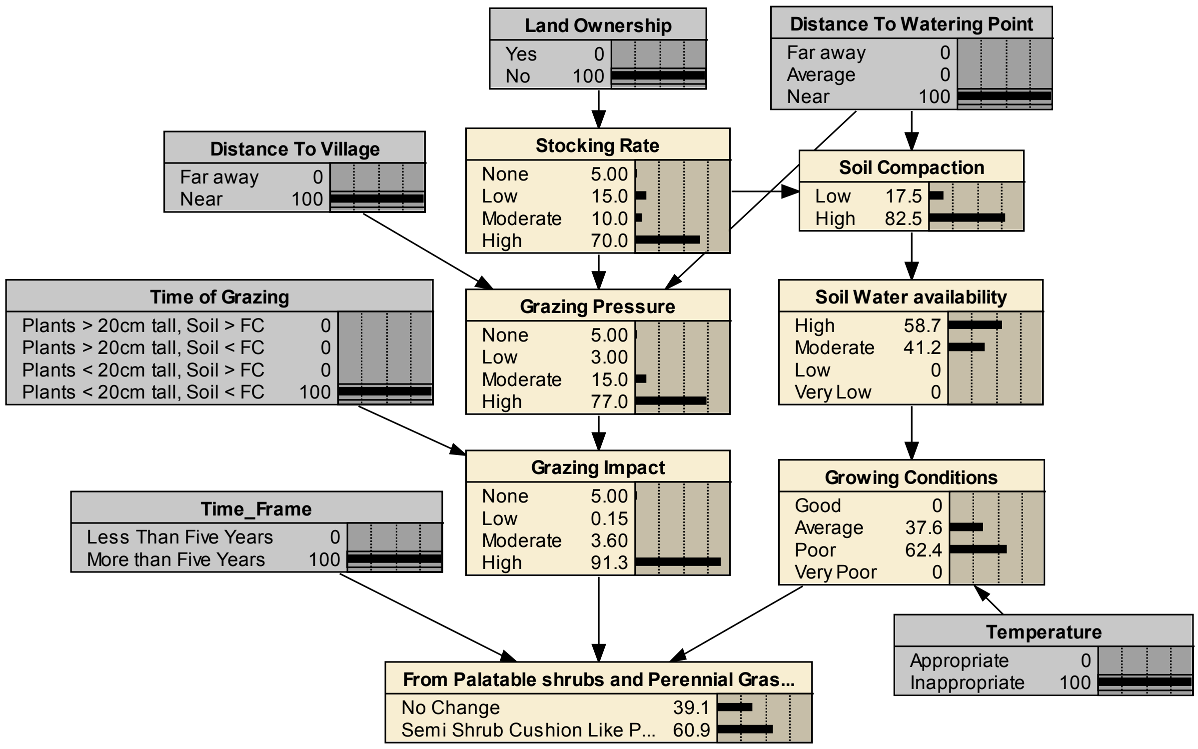

Fig. 5. Prediction using the Steppe zone of Ghom BBN.

Current State	Time_Frame	Grazing Impact	Growing Conditions	No Change	Semi Shrub Cushion Like Per Gr
Palatable shrubs & Perennial gras...	Less Than Five Years	None	Good	100.00	0.000
Palatable shrubs & Perennial gras...	Less Than Five Years	None	Average	98.000	2.000
Palatable shrubs & Perennial gras...	Less Than Five Years	None	Poor	95.000	5.000
Palatable shrubs & Perennial gras...	Less Than Five Years	None	Very Poor	90.000	10.000
Palatable shrubs & Perennial gras...	Less Than Five Years	Low	Good	100.00	0.000
Palatable shrubs & Perennial gras...	Less Than Five Years	Low	Average	95.000	5.000
Palatable shrubs & Perennial gras...	Less Than Five Years	Low	Poor	90.000	10.000
Palatable shrubs & Perennial gras...	Less Than Five Years	Low	Very Poor	80.000	20.000
Palatable shrubs & Perennial gras...	Less Than Five Years	Moderate	Good	90.000	10.000
Palatable shrubs & Perennial gras...	Less Than Five Years	Moderate	Average	80.000	20.000
Palatable shrubs & Perennial gras...	Less Than Five Years	Moderate	Poor	70.000	30.000
Palatable shrubs & Perennial gras...	Less Than Five Years	Moderate	Very Poor	60.000	40.000
Palatable shrubs & Perennial gras...	Less Than Five Years	High	Good	80.000	20.000
Palatable shrubs & Perennial gras...	Less Than Five Years	High	Average	70.000	30.000
Palatable shrubs & Perennial gras...	Less Than Five Years	High	Poor	40.000	60.000
Palatable shrubs & Perennial gras...	Less Than Five Years	High	Very Poor	30.000	70.000
Palatable shrubs & Perennial gras...	More than Five Years	None	Good	100.00	0.000
Palatable shrubs & Perennial gras...	More than Five Years	None	Average	98.000	2.000
Palatable shrubs & Perennial gras...	More than Five Years	None	Poor	95.000	5.000
Palatable shrubs & Perennial gras...	More than Five Years	None	Very Poor	90.000	10.000
Palatable shrubs & Perennial gras...	More than Five Years	Low	Good	100.00	0.000
Palatable shrubs & Perennial gras...	More than Five Years	Low	Average	95.000	5.000
Palatable shrubs & Perennial gras...	More than Five Years	Low	Poor	90.000	10.000
Palatable shrubs & Perennial gras...	More than Five Years	Low	Very Poor	80.000	20.000
Palatable shrubs & Perennial gras...	More than Five Years	Moderate	Good	90.000	10.000
Palatable shrubs & Perennial gras...	More than Five Years	Moderate	Average	80.000	20.000
Palatable shrubs & Perennial gras...	More than Five Years	Moderate	Poor	60.000	40.000
Palatable shrubs & Perennial gras...	More than Five Years	Moderate	Very Poor	50.000	50.000
Palatable shrubs & Perennial gras...	More than Five Years	High	Good	70.000	30.000
Palatable shrubs & Perennial gras...	More than Five Years	High	Average	60.000	40.000
Palatable shrubs & Perennial gras...	More than Five Years	High	Poor	20.000	80.000
Palatable shrubs & Perennial gras...	More than Five Years	High	Very Poor	0.000	100.00

Table 5. Full conditional probability table for “From palatable shrubs & perennial grasses” state relating “Time frame”, “Grazing impact” and “Growing conditions” to possible transitions. In this example, probabilities for the first row is read from the table as, when current state is “Palatable shrubs and perennial grasses”, “Time frame” is less than five years, “Grazing impact” is none and “Growing condition” is good, there is 100 % chance of “No changes” and 0% chance of a transition to “Semi shrub cushion-like plant & perennial grasses”.

Besides answering the "what if" questions the BBN model can also help to answer "how" questions. For example, how might a manager move from an "Semi shrub and cushion like plants" to a "Palatable shrubs and perennial grasses"? Figure 6 is an example of the Steppe zone of Ghom BBN being used to answer this question using diagnosis. The model shows that within a less than five year time frame, this transition is most likely if there is no grazing impact and also good growing condition (see the "Grazing impact" and "Growing condition" nodes), and this is most likely to be achieved by destocking (see the "Stocking rate" node). The model also shows that, more than average rainfall and appropriate temperature are important to achieving good growing condition (see the more than average in the rainfall and appropriate for temperature nodes).

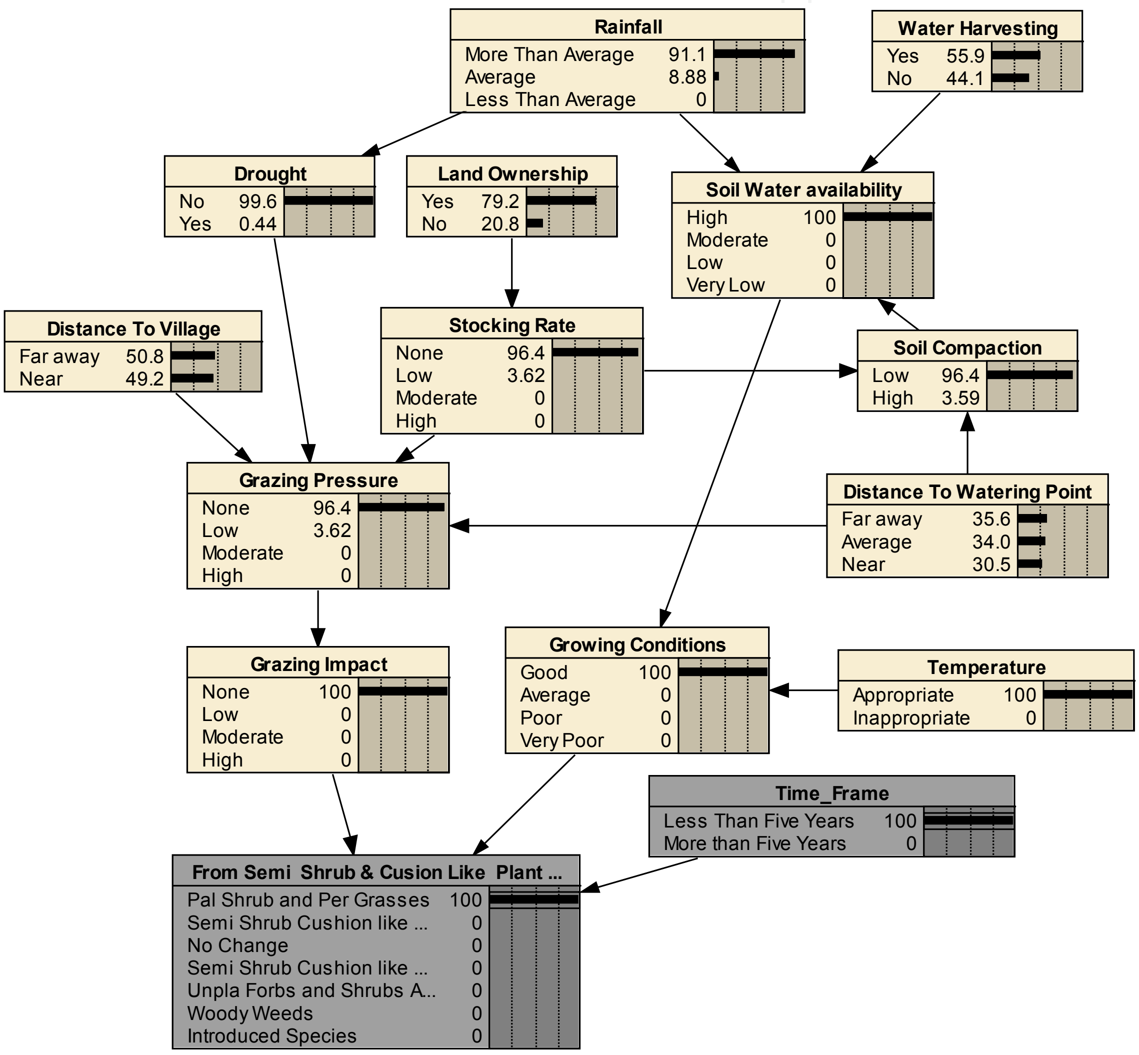

Fig. 6. Using the model for diagnostic assessment to determine the most likely causes of a transition.

3. Conclusion

The methodology used in this chapter (integrating the STM with the BBN) can provide a useful approach to accommodate uncertainty in highly uncertain systems (e.g. Iranian rangeland). Despite the advantage of STMs, they are traditionally descriptive diagrams and are unable to be used for predictive modelling and scenario analysis. They also handle uncertainty associated with causes of vegetation change poorly. Bayesian Belief Network (BBN) used in this study assist in the development of a dynamic and predictive STM by providing a graphical modelling framework for building a probability-based cause and effect model. The results indicated that the BBN approach is a highly useful mechanism for adding value to descriptive STMs. First, it allowed the uncertainty in transitions to be expressed by using probabilistic relationships. Second, the approach provided a scenario and sensitivity analysis tool for both scientists and landholders to assess the probable vegetation outcomes of rangeland management decisions, and to identify those management options most likely to improve or degrade vegetation condition. Third, it is particularly complementary to the adaptive management process, because monitoring records can be used to update probability relationships within the BBN model over time. Therefore, the modelling approach supported the planning, monitoring and review steps of the adaptive management cycle. This is an advantage over current rangeland management simulation models that are good at supporting management planning through their predictive capabilities, but poor at supporting monitoring and evaluation steps.

4. Acknowledgment

I am grateful to Mr Seied Mehdi Adnani and Hossein Bagheri from natural resources and animal affairs research centre of Ghom province and Dr. Hossein Barani from Gorgan University for their participation in the workshops associated with this study and the sharing of their expert knowledge and also to professor Ockie Bosch and Dr. Carl Smith from the University of Queensland for their assistance in this study.

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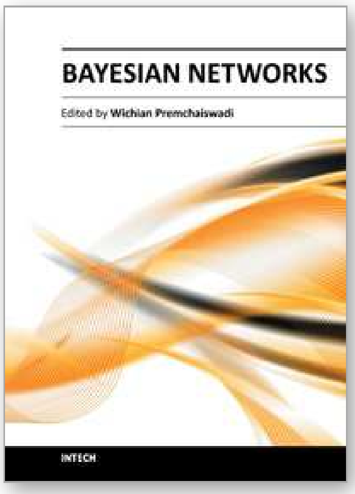

Bayesian Networks
Edited by Dr. Wichian Premchaiswadi

ISBN 978-953-51-0556-5
Hard cover, 114 pages
Publisher InTech
Published online 20, April, 2012
Published in print edition April, 2012

Bayesian Belief Networks are a powerful tool for combining different knowledge sources with various degrees of uncertainty in a mathematically sound and computationally efficient way. A Bayesian network is a graphical model that encodes probabilistic relationships among variables of interest. When used in conjunction with statistical techniques, the graphical model has several advantages for data modeling. First, because the model encodes dependencies among all variables, it readily handles situations where some data entries are missing. Second, a Bayesian network can be used to learn causal relationships, and hence can be used to gain an understanding about a problem domain and to predict the consequences of intervention. Third, because the model has both causal and probabilistic semantics, it is an ideal representation for combining prior knowledge (which often comes in a causal form) and data. Fourth, Bayesian statistical methods in conjunction with Bayesian networks offer an efficient and principled approach to avoid the over fitting of data.

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Hossein Bashari (2012). Making a Predictive Diagnostic Model for Rangeland Management by Implementing a State and Transition Model Within a Bayesian Belief Network (Case Study: Ghom- Iran), Bayesian Networks, Dr. Wichian Premchaiswadi (Ed.), ISBN: 978-953-51-0556-5, InTech, Available from: http://www.intechopen.com/books/bayesian-networks/making-a-predictive-diagnostic-model-for-rangeland-management-by-implementing-a-state-and-transition