BELIEF NETWORKS: A FRAMEWORK FOR THE PARTICIPATORY DEVELOPMENT OF NATURAL RESOURCE MANAGEMENT STRATEGIES

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Abstract. Successful long-term management of natural resources requires the development of strategies which recognise the constraints pertaining to the environmental system and can therefore be realistically expected to work. This paper presents a new technique for strategy formulation using belief networks, a framework based on Bayesian probability calculus that supports the investigation of complex environmental systems by the user and analysis of all constraints. While mathematical in nature, belief networks are superficially simple and allow concepts to be expressed in terms with which a wide range of user will be familiar. This offers a participatory approach to the development of management strategies through consideration of the impact of potential management options with consequent benefits for strategy implementation.

Key words: Bayesian belief networks, integrated natural resource management, participatory management, stakeholder involvement.

1. Introduction

It is widely accepted that the management of natural resources should aim to benefit all resource users as equitably as possible, within the constraint of sustainability (environmental, financial and institutional). Such multi-objective management approaches have been termed Integrated Natural Resource Management (INRM) strategies (Batchelor, 1995). Experience in Australia and South Africa (e.g. Blackmore, 1995) has shown that, ideally, INRM is comprised of three components – the formulation of management strategies, the implementation of those strategies and monitoring procedures to assess whether the impacts are those intended and to adapt the strategies accordingly. This paper presents a novel approach to management strategy formulation which can help achieve INRM objectives.

One formal approach to developing environmental management strategies involves two steps. Firstly, the management options available are identified and secondly, decisions are made as to whether these options should be implemented. These decisions will not only be made at the beginning of a project but throughout its lifetime in response to monitoring and evaluation of project progress and changes in the environmental system. To support INRM, such decisions should be based on an assessment of this system as a whole. Viewed holistically, the system consists of all the factors which interact with the resource to be

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managed together with the variables that characterise these interactions. It is clear that these variables must represent a range of physical, economic, institutional, social, political and cultural factors. Sound management strategies will be based on some understanding of how these variables act and interact as a whole to constrain and provide opportunities for development.

As environmental systems are highly complex, however, developing such an understanding is difficult. In general terms, two analytical approaches to doing this can be identified. On the one hand, a ‘discursive’ approach can be used which is highly detailed, descriptive and locally specific (Martin, 1999). On the other, a more quantitative, mathematical approach can be employed to create simpler models which can be applied more generally (O’Callaghan, 1995). Using either approach, it is inevitable that there will be a significant degree of uncertainty associated with the understanding obtained. It is important, therefore, that optimal management strategies must account for this uncertainty when potential management options are selected.

However, understanding the system is not enough; practical improvements in resource management are needed. A failing of many INRM strategies has been that, while they have been able to formulate plans on an integrated basis, the plans have not been applied successfully (Blackmore, 1995; Van Zyl, 1995). One of the main reasons for this is that management plans are generally developed without the participation of local individuals and institutions, and so do not understand the motivations of these important groups. The resulting lack of stakeholder co-operation undermines any delivery mechanisms designed to implement the management plan and the potential benefits fail to be realised. A first step in overcoming this barrier is to encourage stakeholder involvement in plan formulation. This involvement is facilitated by a user-focused planning procedure, accessible to people with a wide range of ability, which highlights the consequent benefits of plan implementation.

Belief networks provide an approach to holistic formulation of management plans by supporting a mathematically based analysis of environmental systems while not excluding a more descriptive approach. Moreover, they allow uncertainty in decision making to be explicitly accounted for and their superficial simplicity facilitates the participation of a wide variety of people.

2. Belief Networks

Bayesian Belief Networks (BBNs) were originally developed as a formal means of analysing decision strategies under uncertain conditions (Varis, 1997a). Uncertainty is accounted for by using Bayesian probability theory which allows subjective assessments of the chance that a particular outcome will occur to be combined with more objective data quantifying the frequency of occurrence. BBNs have been applied to a number of different problems (Jensen, 1996), although only recently to the field of environmental modelling (Stassopoulou et al., 1998; Varis, 1997a,b). This section will use an example to illustrate how Belief networks can be constructed to facilitate stakeholder involvement in the development of INRM plans.

The foundation of the network is a cause and effect diagram which represents system variables as boxes and the interactions between them as arrows, the direction of which indicates the flow of cause and effect. Variables can represent anything that the user considers to be important in the environment of interest. For example, a model can be constructed to conceptualise the perceived influence of rainfall on harvest simply by connecting a box representing rainfall to one representing harvest (see Figure 1). The user can then define the states that each variable might take as he or she sees fit. For example, the variable ‘rainfall’ might be given states defined by recorded amounts in millimetres per month, states of ‘high’ or ‘low’ or, alternatively, ‘enough to fill the well’ and ‘not enough’. This choice can be made by the user so that his or her perceptions can be described in a way which is as natural as possible.

The diagram that is constructed in this manner provides a conceptual diagram or static representation of the perceived environmental system. While the diagram expresses the perception that there is an interaction between variables (simply by the presence of the arrow) the nature and strength of that interaction must be expressed by specifying how the arrows function. Conceptually, a change in the state of the variable at the tail of an arrow (called the parent) causes an effect on the variable at the point of the arrow (called the child). This effect is quantified by assigning a probability that a child variable will be in a particular state given the state of any parent variables.

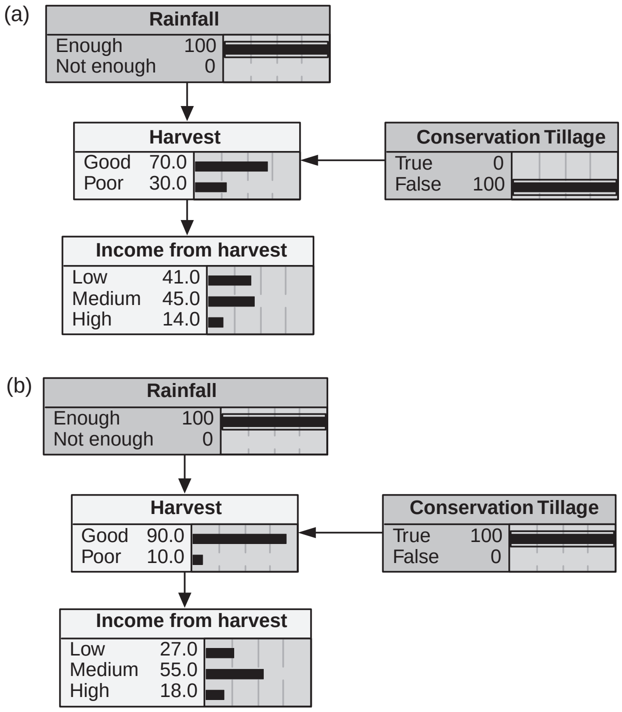

Figure 1. Simple belief network showing expected income from harvest if conservation tillage is (a) not used and (b) used.

For example, in the simple example above, the parent ‘rainfall’ influences the child ‘harvest’. Imagine now that ‘rainfall’ has been given the states ‘enough to fill the well’ and ‘not enough’ by the user and that ‘harvest’ has been given the states ‘good’ and ‘poor’. If the state of ‘rainfall’ is ‘enough to fill the well’, the user might believe, based on his or her experience, that the chances of the ‘harvest’ being ‘good’ are about 7 in 10. In this case, therefore, a probability of 0.7 (or 70%) would be assigned to this combination of states (the repetitive use of quotes indicates how such information could be elicited through interviewee and participatory survey techniques). Other probabilities can be identified similarly (see Table I). This information is then incorporated into the network in the form of a conditional probability table expressing the probabilities that ‘harvest’ will be in a particular state conditional on the state that ‘rainfall’ is in, as shown in Table I.

However, the interactions between variables do not have to be specified in the subjective manner presented in Table I. Cases may arise when relationships between environmental variables can be collected more objectively. For example, If ‘harvest’ is related to a new variable, ‘revenue from harvest’, then the relationship between the two could be defined using local market prices or revenues generated from harvests in previous years. Of course, market prices fluctuate and previous years are no guide to the future. However, a probability distribution (perhaps based on the standard deviation of the data set) could be derived from the real revenue data to represent an objective belief in how these variables interact. Consequently, any uncertainty in the relationships between the environmental system variables in the model can be accounted for. Furthermore, if the user feels that this gives, say, an overly optimistic assessment of certainty in the relationship between variables in the model then the distribution can be widened until he or she is satisfied it represents their perception of the uncertainty.

Once constructed, the model can be used to investigate how the system might respond to potential management options (the introduction of new conservation tillage practices, for example). This is done by introducing a variable to represent the option of interest and changing its state to see how this affects the states of the other variables in the network.

An example network, constructed using the Netica software package (Norsys Corp., Canada), is presented in Figure 1, which shows the modelled outcome of introducing new conservation tillage practices (the example is included for purely illustrative purposes and is not based on real data). According to this particular conceptual model, rainfall and land

TABLE I. Conditional probability table for the relationship between rainfall and harvest. Read as, for example, ‘if rainfall is enough to fill the well, then there is a 7 in 10 chance that the harvest will be good’

Rainfall	Harvest	
	Good	Poor
Enough	0.7	0.3
Not enough	0.1	0.9

management practice affect the harvest which, in turn affects the farm's income. These, then, are the four variables. The states of each variable are shown, with the probability distributions over them indicated both numerically and graphically, by the bar chart (e.g. there is a 70% probability that 'harvest' is in the state 'good'). In Figure 1a, the expected income (an average value) perceived to result from the case when rainfall is enough, but conservation tillage is not practised, is shown (the units are in some unspecified currency). Figure 1b shows how the income might change if conservation tillage was introduced. It can be seen that the expected income increases from 12.3 to 14.1 and that the probability distribution surrounding this average value also changes.

These changes in outcome are accomplished through mathematical algorithms which update the beliefs associated with each variable state. Further details of how this is achieved are given by Spiegelhalter et al. (1993) and Jensen (1996). It must be stressed that, while the software makes this process much quicker and easier, it is only a tool (like a specialised calculator) and is not essential. A computer is not required to draw the networks nor to specify how the relationships function and merely makes the investigation of the effects of any system changes quicker. The method by which the information required for the analysis is solicited and the outputs from the analysis are communicated, is entirely independent of whether computer software is used or not. The technique is the key – not the software.

3. Application of Belief networks to INRM plan formulation

The example above illustrates how Belief networks can be used to examine the impacts of potential management options on an environmental system as a whole. It does this by 'capturing' the perceptions of each user and allowing the implications of their conceptual model to be investigated.[1] As such, any model created is not an objective or definitive model but represents the perception of the user at the point in time when a decision has to be made.

Belief networks can, consequently, be used at two levels. Firstly, by enhancing the human mind's capacity to consider multiple factors simultaneously and in a structured way, Belief networks will allow environmental managers to investigate the impact (as they perceive it) of their favoured management options on the environment as a whole. Secondly, stakeholders can mirror this process and so communicate their perceptions as to the impacts of potential management strategies and, additionally, suggest their own. This is crucial as human perception plays a crucial role in the definition of any environmental resource system. Depending on their background, interests and experiences, different people will have different ideas about how the system works and to what degree changes can improve things or make things worse. Stakeholder perception is, therefore, a key catalyst or impediment to change in any system and must be understood by an environmental manager if successful strategies are to be formulated.

In practice, enabling non-specialist stakeholders to construct Belief networks will not be straightforward. The accessibility of Belief networks, however, and their facility to use subjective data, allows a conceptual model of a system to be created which is relatively close to a user's description of that system (Browne et al., 1997). The graphical part of the network can be constructed by a range of stakeholder groups (for example, women and men, young and old, livestock owners, district level decision makers etc.) so that any differences in perception of ownership and entitlement to the common property resource system between groups can be identified. It is important that this process is facilitated by a skilled person who can elicit the necessary information without imposing his or her own beliefs. The facilitator can encourage stakeholders to identify all the factors which they feel impact their resource base and livelihood strategies and explain how they understand them to interact in terms of cause and effect.

One constraint in doing this, is that it becomes difficult to implement the mathematical algorithms when the Belief network becomes too large and the links between the variables are many and complex. In practice, however, this can often be an advantage in that it forces the user to focus on the key variables within the system which have the greatest impact.

A completed diagram (i.e. a network before the specification of the conditional probabilities) can then be used as a basis for subsequent household or group surveys to provide the data for the conditional probability tables. These surveys would be designed to elicit any further information that may be required to specify how the relationships operating in the natural resource base, as identified by the users themselves, actually function. In this manner, household surveys and participatory group exercises which aim to obtain more information about the natural resource system can be guided and designed iteratively with the user community. Moreover, by using this procedure, data collection can be made as effective and efficient as possible.

Once the information has been collected, fully completed networks can be run by different user groups to examine the effects of various management options on the resource base. The outputs provided by the technique could be presented in a variety of ways as appropriate to the requirements of the stakeholder group. If the effects shown by the network do not tally with what the stakeholder group considers to be realistic, then the structure of the network and the information on which it is based can be re-examined and adapted as seen to be appropriate. It may be that a particular assumption on the part of the stakeholder group led to an unexpected result and, if this is the case, then this assumption may be wrong. The network may help to correct poor assumptions by encouraging conceptual consistency but, when assumptions are judged to be valid, may lead to unexpected conclusions.

While not specifically using Belief networks, work carried out by Lynam (1993) with poor farmers in the Zambezi valley, has demonstrated how techniques such as those described above can be used to provide information for mathematically based decision support tools. When used in this way, Belief networks will allow stakeholders to judge the likely impact of their favoured management options on the environment as a whole. By doing this, they can reach their own conclusions as to which of these options are most likely to succeed. Moreover, as they provide a common format for discussion, Belief networks allow the process by which decisions were reached to be communicated and provide others with an opportunity to examine the underlying assumptions. This will allow environmental managers (and others) to deduce the different interests and driving forces of each stakeholder group (which may not always be motivated by the common good). With careful facilitation, this may result in a consensus solution. If this is not possible, then the environmental manager will, at least, be able to make a decision based on a detailed understanding of the system, informed by stakeholder perception and aware of the uncertainties involved.

It must be stressed that decisions made using this approach should not be considered binding nor constitute a project ‘master plan’. As a decision must be made at a single point in time, the Belief networks on which it may be based represent only the knowledge which is available to the decision maker at that time. Clearly, environmental state and peoples’ perceptions will change with time (especially in response to implementation of a management plan) and strategies should be adapted to account for this. As these changes will often be unpredictable, it is important that effective monitoring and evaluation procedures are designed to detect them. Specification, prior to implementation, of what constitutes unacceptable change, provides an objective means of judging the effectiveness or otherwise of management strategies. Where old strategies are seen to be failing new strategies should be developed.

The level of consultation required to use this approach to management planning encourages transparency, which is vital if resulting management strategies are to be trusted and accepted. Using such an approach increases the likelihood that the implementation phase of an INRM strategy will be successful.

4. A case study from India

To test their utility for INRM plan formulation, a Belief network was used to examine the expected impact of the management options being implemented by a watershed development project in Karnataka, India, which had already been running for a year. Through discussion with one of the project designers, it was identified that the prime objective of the project was alleviation of poverty and that the three main project activities were:

1. Facilitation to improve community empowerment
2. Improved soil and water conservation to increase availability of resources
3. Better advice to encourage development of appropriate productive skills

Based on this, a Belief network was constructed, as shown in Figure 2, composed of the prime objective, the three activities above and additional variables which were considered to mediate the impact of those activities on the prime objective. While the project designer was well aware of the huge number of additional factors that influence the success or failure of the project, he was asked to select only those which he considered to be of primary importance.

The probability distributions for the variables ‘Facilitation’, ‘Social cohesion’, ‘Rainfall’ and ‘Quality of advice’ (root variables) were specified based on the project designer’s subjective assessment of the likely state of each (the 50–50 split for ’Quality of advice’ indicates that he did not know). The conditional probability tables (expressing the state of child variables based on the states of their parents) were also specified using the subjective judgements of the project designer. Table II gives an example of the table created for the variable ‘Community empowerment’. Together the root variable probabilities and conditional probabilities allowed the probabilities of the other variables to be calculated.

Constructed in this way, the network represented the subjective perception of the project designer. Consequently, it allowed him to investigate the implications of his conceptual

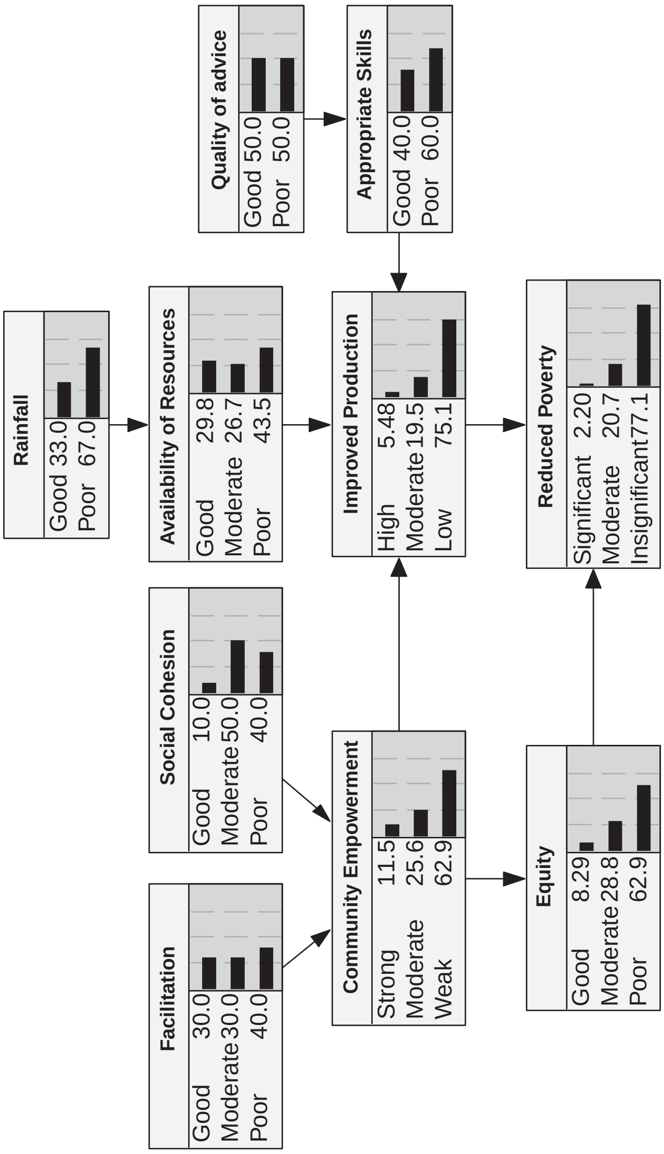

Figure 2. Belief network representing a development project in India.

TABLE II. Conditional probability table for ‘Community empowerment’ variable. Read as, for example, ‘if facilitation is good and social cohesion is good, then there is a 5 in 10 chance that community empowerment will be strong’

Facilitation	Social cohesion	Community empowerment		
		Strong	Moderate	Weak
Good	Good	0.50	0.40	0.10
Good	Moderate	0.40	0.40	0.20
Good	Poor	0.20	0.30	0.50
Moderate	Good	0.20	0.40	0.40
Moderate	Moderate	0.05	0.40	0.55
Moderate	Poor	0	0.20	0.80
Poor	Good	0.05	0.30	0.65
Poor	Moderate	0	0.20	0.80
Poor	Poor	0	0	1.00

model by varying the states of variables representing the management options and observing the effect this had on the variable representing poverty reduction. As shown by Figure 2, the network indicated that, when perceived in this limited way, the immediate impact of the project was likely to be insignificant. It must be stressed that this result is purely a consequence of the project designer’s perception of how the limited system represented by the Belief network works and the likely strength of the interactions between the variables. It is in no way a prediction of what will, or even what may, occur. The Belief network has merely allowed the designer to structure his decision problem and, by doing so, reveal an unexpected conclusion.

By altering the states of the network, the designer could further investigate his conceptual model and seek possible ways of improving project implementation. As ‘Facilitation’ and ‘Quality of advice’ were the two variables that could most easily be controlled by external influence, it was of interest to observe the impact of changing them. Even with the variables representing facilitation and quality of advice set as optimistically as possible, however, the designer’s belief that poverty would be significantly reduced only rose to 5.3% (from the 2.2% shown in Figure 2).

This analytical process, offered the designer an approach for identifying potential weaknesses in the management plan and investigating them. One conclusion from the analysis above is that the Belief network did not show a significant reduction in poverty as too many additional factors which would impact on the objective had been ignored. In that case, the Belief network would provide a formal framework within which additional factors could be identified, added to the network and their impact on the objective observed.

In one sense, the actual change observed in the objective variable is irrelevant. For project design, consideration of the interactions highlighted by the Belief network may be more useful. For example, in this case, analysing the network revealed that the designer did not believe that facilitation would achieve community empowerment alone as social cohesion was not good enough. This interaction between three variables had not been clearly identified before due to the difficulty in considering this complex system without a tool to help (even for a simple system as constructed here). By facilitating such considerations, the Belief network was able to reveal some useful new information.

The test is limited in that it was performed with a single stakeholder (the project designer) and no element of stakeholder discussion was introduced. It did serve, however, to demonstrate how an individual's perception can be captured by a Belief network and used as a conceptual model to investigate perceived consequences of potential management options.

5. Conclusions

Management of natural resources is generally achieved by a combination of experience, intuition, trial, error and effort. This may be successful but is not a basis for effective long term resource management systems which are essential to improved management practice. As currently formulated, however, many management plans are little more than a static list of desirable objectives.

Belief networks explicitly recognise the complexity of environmental systems and allow consideration of all key system variables together with their impacts on the environment. Importantly, this can be done in a descriptive manner which supports stakeholder participation and provides the potential to help resolve conflicts between stakeholder groups. As such, they provide a means by which comprehensive environmental plans can be developed dynamically so that they might realistically be expected to contribute to better management of natural resources.

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Notes

[1] To be clear, each individual's representation of the system, no matter how that may be perceived or expressed, will be termed a conceptual model.

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