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Bayesian belief modeling of climate change impacts better informs regional adaptation options

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Abstract

A sequential approach to combining two established modeling techniques (systems thinking and Bayesian Belief Networks; BBNs) was developed and applied to climate change adaptation research within the South East Queensland Climate Adaptation Research Initiative (SEQ-CARI). Six participatory workshops involving 66 stakeholders based within SEQ produced six system conceptualizations and 22 alpha-level BBNs. The outcomes of the initial systems modeling exercise successfully allowed the selection of critical determinants of key response variables for in depth analysis within more homogeneous, sector-based groups of participants. Using two cases, this article focuses on the processes and methodological issues relating to the use of the BBN modeling technique when the data are based on expert opinion. The study expected to find both generic and specific determinants of adaptive capacity based

on the perceptions of the stakeholders involved. While generic determinants were found (e.g. funding and awareness levels), sensitivity analysis identified the importance of pragmatic, context-based determinants, which also had methodological implications. The article raises questions about the most appropriate scale at which the methodology applied can be used to identify useful generic determinants of adaptive capacity when, at the scale used, the most useful determinants were sector specific. Comparisons between individual BBN conditional probabilities identified diverging and converging beliefs, and that the sensitivity of response variables to direct descendant nodes was not always perceived consistently. It was often the accompanying narrative that provided important contextual information that explained observed differences, highlighting the benefits of using critical narrative with modeling tools.

1   Introduction

Our responses to climate change are becoming more varied. In addressing the current and projected impacts of climate change, governments, policy makers and researchers have emphasized the mitigation of climate effects through emission reduction strategies, both economic and technical, and predicting how biophysical systems will respond to climate change (Lorenzoni et al., 2000; Ford et al., 2006). While these responses are crucial to addressing the drivers of climate change, it has been recognized for some time that there is also a need to adapt to climate change: to manage unavoidable risks, reduce people's vulnerability, and to build resilience to minimize impacts on communities (IPCC, 2007). It is now acknowledged that, in contrast to mitigation, the formulation of adaptation strategies requires a deeper understanding of the human dimensions of climate change impacts and that successful adaptation strategies need to be underpinned by the assessment of the adaptive capacity of communities of place and practice (Lorenzoni et al., 2000; Ford et al., 2006). This allows interventions and adjustments at a range of scales and helps institutions formulate context-specific adaptation policies and measures that can reduce vulnerability (Preston and Stafford-Smith, 2009).

Routinely available physical, demographic and economic data have been the foundation of most adaptive capacity assessments (e.g. Swanson et al., 2007), because they are relatively easy to source (e.g. census surveys). However, adaptive capacity (and responses) are strongly dependent on the perceptions of the 'agents' acting within a system (Adger, 2003) and on context-specific circumstances, which are not captured readily by accessible, quantitative indicators (Roiko et al., 2012). Trans-disciplinary and flexible approaches to the integrated assessment of global change and adaptation responses are needed to account for the complexity inherent within linked socio-ecological and economic systems (Valkering et al., 2009). We present here an approach to identifying the social, economic and environmental

determinants of adaptive capacity in response to climate change, with some methodological lessons that emerged.

The method applied combined two established modeling techniques: systems thinking (Forrester, 1968; Checkland, 1981; Senge, 1990; Sterman, 2000) and Bayesian Belief Networks (BBNs) (Charniak, 1991; Varis and Kuikka, 1997; Kjaerulff and Madsen, 2008). Both are suited to assessing climate change adaptation when there are limited data because they facilitate direct involvement of stakeholders, cater for both deductive and inductive logic, and explicate stakeholder mental models, with their probable, causal relationships, that form the basis for actions of stakeholders. The methods are also complementary. Systems thinking provides a framework for systems practice, a way of thinking holistically about real problems and modeling complex systems (Sterman, 2000), while BBNs can account explicitly for uncertainty, even when limited by sparse datasets, through eliciting qualitative variables from 'expert opinion' (Charniak, 1991; Castelletti and Soncini-Sessa, 2007; Aguilera et al., 2011). They are particularly useful for providing a structured framework for integrating disparate types and sources of knowledge (published material, stakeholder and expert experience) in data-poor and knowledge-vague settings (Chaloupka, 2007). Hence, systems thinking can make explicit conceptualizations of the key elements of a socio-ecological system, while Bayesian networks can address causality (probabilistically) with estimated likelihoods and consequences of nested determinants.

This sequential modeling approach was developed and applied to climate change adaptation research within the South East Queensland Climate Adaptation Research Initiative (SEQ-CARI). SEQ-CARI is a cross-sectoral and trans-disciplinary project that seeks to inform decision-makers at different levels (local, state, federal) of government about the region's adaptive capacity and adaptation options to climate change. Systems thinking was used (1) to develop a common understanding of the system relating to climate change impacts, and (2) as

a mechanism to identify leverage points in the system that participants regard as crucial for addressing the impact of climate change. BBNs then were used to explore these 'key leverage variables' to specify, clarify and assess the range of beliefs relating to individual and community capacity to affect change. The findings of the BBN will be used to develop strategies to build adaptive capacity within and between the various sectors that may be affected by climate change in SEQ. Furthermore, the findings will also help to validate and refine climate change adaptation options for the region; which are often developed in isolation to comprehensive assessments of adaptive capacity (Measham et al., 2011; Smith et al., 2011).

2 Methodology and materials

2.1 The study area

South East Queensland (SEQ), one of the fastest growing areas in Australia, is the study area for this research. This region covers 22,420 square kilometres and incorporates eleven local authorities, including the capital of the State, Brisbane, which has approximately two million inhabitants. The SEQ region has experienced considerable population growth over the last 40 years, increasing from around 1.4 million in the early 1980s to a current population of approximately three million, and is projected to rise to 4.2 million over the next 20 years (Queensland Department of Infrastructure and Planning, 2008). Most of the current population is concentrated in Brisbane, and spreads along the coast northward, ca 80 km, to the Sunshine Coast area, and southward, ca 70 km, to the Gold Coast area.

2.2 The modeling methods

The research used system conceptualization as a first step in model development to provide insight into the determinants of adaptive capacity to human-induced climate change.

Stakeholders from the study region used participatory modeling techniques (systems thinking and BBN) to develop mental models and BBNs based on their beliefs. We chose specific software (Vensim and Netica) because of past success in their use in participatory modeling exercises (Smith et al., 2009; Voinov and Bousquet, 2010) although other systems thinking (e.g. STELLA www.iseesystems.com) and BBN (e.g. Hugin www.hugin.com) software options are available. In addition, other integrative modeling techniques such as agent-based (Berman et al., 2004) and agent-based 'game' models (Valkering et al., 2009) have been used with success in modeling sustainability of systems.

2.3   Stakeholder workshops

The models were developed through six participatory workshops conducted at the end of 2010. These workshops focused on different settlement types and sectors across the study area (Table S1 - supplementary material). They included 66 stakeholders (representatives of selected government agencies, NGOs and the private sector) working in climate change adaptation management and/or policy development. The workshops addressed four settlement types (three different types of coastal settlements and one land-locked master-planned community) and two sectors (coastal conservation and energy). These were considered representative of many of the salient climate change issues for the region.

Model development involved a repeated two-stage process at each workshop consisting of (1) a system conceptualization, and (2) construction of BBNs focused on a selected 'priority issue'.

2.4   System conceptualization

Conceptualization of a system based on stakeholder mental models is a fundamental precursor step in addressing the identification of critical issues within the system. The use of

systems thinking approaches that apply participatory techniques to map systems understanding has emerged in the last two decades from the work of various authors (e.g. Senge, 1990; Richardson and Andersen, 1995; Sterman, 2000), and examples of practical applications are common in the literature (Antunes et al., 2006; Elias, 2008). Participatory systems approaches are commonly applied in urban and regional planning and natural resource management with established techniques to capture information from stakeholder groups (reviews include Mendoza and Prabhu, 2006; Lynam et al., 2007; Voinov and Bousquet, 2010). In our research, we adapted techniques successfully applied by Smith et al., (2009) to explore the mental models of diverse stakeholders to construct a collective system conceptualization and to identify critical elements/nodes within the system for further examination using Bayesian belief network modeling.

Each workshop, lasting approximately one hour, commenced with workshop participants being provided with contextual information about the SEQ-CARI project, including an overview of the salient issues related to climate change in their area or sector of concern. A suite of specified climatic and non-climatic 'drivers' (e.g. sea-level rise, increased storm intensity, population growth) was then presented to prompt the group system conceptualization model building process. Stakeholders were asked to identify the social, economic and environmental factors they believed were associated with these initial drivers. The developing system conceptual model was simultaneously replicated on a large sheet of paper that the participants could observe and on a computer using the software platform Vensim (www.vensim.com). This leads to a shared mental model of the 'system' that allows its exploration at local and sectoral levels using the collective knowledge of the workshop participants. The system conceptualization process was directed by a lead facilitator responsible for stimulating the group in identifying the elements and connections of the system, helped by the structural analysis tools embedded in the software.

2.5   Development of BBNs

The second stage of the model-development process involved using the system

conceptualization as a mechanism for identifying 'priority' management issues (representing

adaptive capacity of the system) and the variables influencing them (determinants of adaptive

capacity). BBN modeling (Charniak, 1991) is a methodology well-suited to representing the

causal relationships of a system in the context of variability, uncertainty and subjectivity

although they have been used infrequently within the environmental sciences (Aguilera et al.,

2011). They have a demonstrated utility for eliciting subjective expert opinion (Lynam et al.,

2007; Uusitalo, 2007), dealing competently with missing or sparse data (Uusitalo, 2007),

facilitating participatory model-development (Castelletti and Soncini-Sessa, 2007) and

providing a framework for model improvement (updating) as new data and knowledge

become available (Ordóñez Galán et al., 2009). They also provide a framework for

combining knowledge/data from different sources and of different accuracies (Uusitalo,

2007), including the capacity to integrate social, economic and environmental variables

within a single model. The utility of BBNs for eliciting expert opinion through both network

development and populating conditional probability tables (CPTs) is also well-established

(Castelletti and Soncini-Sessa, 2007; Uusitalo, 2007; Kjaerulff and Madsen, 2008).

To begin the BBN development process, stakeholders from the four cross-sectoral workshops

were separated into pre-determined sectoral groups, while for the sector-specific workshops

they were separated into sub-groups based on the criterion that each contained at least three

participants. Each stakeholder group selected a priority issue from within their system

conceptualization that represented the issue most relevant to their role relating to climate

change and adaptive capacity. The stakeholders were then provided with a framework for

developing the BBN structure (Varis and Kuikka, 1997) based around the selected priority issue.

Stakeholders were first instructed to assign two states to their priority issue: a desirable state and an undesirable state, thereby creating a discretized variable. Simple examples, unrelated to climate change adaptation, were provided with 'rules' that underpin BBN discretization (Uusitalo, 2007). That is, the states must be consistent for the variable, address all possible outcomes and be mutually exclusive.

Workshop participants were then prompted with the focus statement:

"Identify primary variables that directly influence your current capacity to manage this priority issue"

The stakeholders then brainstormed a set of primary variables, selecting the three most important ones for inclusion in the structure of the BBN. The first level of causality in the diagram was developed through this process (Figure 1). The participants then were asked to discretize the primary-level variables by assigning two states to each, again highlighting the key requirements of consistent, comprehensive and mutually exclusive states.

The follow-up focus statement, which emphasized direct causality, then was posed to the workshop stakeholders as a means of eliciting further hierarchical layers for the network diagram:

"Identify the variables that directly influence these primary variables"

A maximum of three secondary variables were recommended for each of the primary variables (Figure 2) with two states assigned to each. This step represented an iterative process whereby the participants were invited to expand their BBN structure for further

generations using the second question. Stakeholders were allocated 50 minutes to develop their structure.

The requirement of two states only for the priority issue was a strict guideline in the development process. By convention, discrete values were used throughout (instead of continuous states) to ease computation of the BBN, elicitation of expert opinion and the communication of results (Ames et al., 2005). However, this discretization process has the disadvantage of resulting in a coarse representation of the probability distribution (Uusitalo, 2007).

Guidance was also given to the stakeholders regarding the maximum number of parent nodes and discretized states associated with each hierarchical level. This was to avoid large and intractable conditional probability tables (CPTs) during the latter stage of the BBN development (Marcot et al., 2006). However, prudent flexibility was allowed for these hierarchical layers. For example, if the stakeholders provide compelling reasons for the inclusion of four primary variables rather than the recommended three, relaxation of the guidelines was allowed at the discretion of the group-level facilitators who oversaw this phase of the development process.

The discretization of the variables was an important component of the model building process. Marcot et al. (2006) suggest that no more than five states should be assigned to any one variable and that the number selected is a balance between precision and parsimony. Furthermore, the elicitation of expert probabilities can be demanding because the number of permutations increases exponentially as the complexity of the model increases (Shaw et al., 2010). In the context of the qualitative and largely social-economic nature of our BBNs, we chose to favour parsimony over precision and prescribed a maximum of two states for each

variable. The results were typically broad qualitative, often dichotomic, descriptions of the states such as 'high level' and 'low level'.

Conditional probability tables

The developed structure was converted to functional BBNs by populating the associated CPTs using Netica software (Norsys Software, 2008). CPTs quantify the strength of causality between 'parent' and 'child' nodes, taking into account all possible combinations of the 'states' of the parent nodes and the associated probability of observing a particular state for the child node. In contrast to the development of the BBN structure, which was based on the collective belief of workshop participants (group-model building), populating the CPTs was conducted at an individual stakeholder level. This allowed individual probabilities to be compared.

A CPT is required for each variable (child node) that is causally dependent on at least one other (parent) node. Assigning conditional probabilities to the dependent variables can be achieved by training the network to monitoring data and/or model output using algorithms (Spiegelhalter et al., 1993). In the context of social dynamics and climate change adaptation, as outlined in this research, all data used in this study are sourced solely through expert opinion, including populating the CPTs.

CPTs were populated through a combination of one-on-one meetings during and after the workshop and, if face-to-face meetings could not be organized, through email correspondence. The approach used was largely determined by the availability of the stakeholders. Follow-up meetings were preferred as it enabled minor refinements of the BBN structure (e.g. adjustment of the number of states assigned to a variable). To explicitly account for the conditional probabilities elicited from each of the stakeholders we employed conditioning or auxiliary variables (Kjaerulff and Madsen, 2008). Auxilliary variables were

specified for every child node within the BBN structure with the contribution of each stakeholder's CPT weighted equally.

2.6   Narrative capture

Discussions between participants throughout the workshops and comments by individuals during the CPT populating process were recorded manually by members of the research team assigned to this role. This provided a form of narrative capture to give additional context to the modeling process. This included recording comments made about their BBN structure (e.g., rationale for selecting the variables), the probabilities assigned to the CPTs, the level of consensus within the group and about the model development process in general. This information was used to clarify participants' understanding of variables and the relationships between stakeholders prior to and during the follow-up individual interviews used to populate the CPTs.

2.7   Sensitivity analysis

A sensitivity analysis was undertaken on each BBN using Netica. This helps identify which inputs most affect the output and is an important process in model testing, understanding the influential pathways through the developed BBNs (Marcot et al., 2001, 2006; Howes et al., 2009) and, in the context of this study, identifying important determinants of adaptive capacity.

3   Results

We present an overview of the results of the systems conceptualization and BBNs generated from the six workshops, followed by a discussion of two case studies that exemplify methodological issues. The six workshops produced six system conceptualizations and 22 BBNs. During system conceptualization, the participants identified 245 variables. A Vensim

analysis of these variables highlighted the emergence of recurrent and broad issues across workshops, such as the level of funding available and the need for specific policy responses. While these issues can be considered generic and self-evident, participants also identified specific issues that were not visible within the system at first sight. For example, design standards for homes was identified as one of the major triggers for responding to climatic change, with impacts on a large number of sectors, such as energy, health, coastal and emergency management.

From the systems conceptualization, the stakeholders identified twenty-two priority issues (Table 1) that were used as indicators of adaptive capacity. For the four cross-sectoral workshops, there was convergence in the selection of priority issues for the emergency management, health, planning and coastal management work groups. The focus area for emergency management (three of four priority issues identified) was on the resilience and vulnerability of the community. Health focused mainly on community well-being (three of four priority issues), planning focused on sustainable community planning (three of four), and coastal management on the built environment (two of three). Conversely, the four priority issues selected for infrastructure were a mixture of infrastructure funding and design, policy and community well-being. The two priority issues considered during the sector-specific biodiversity workshop were selected intentionally by the researchers to address divergent areas of management concern within this sector (*Functionality of ecosystems* and *Impact of development on marine and coastal areas*). Finally, the single priority issue selected for the energy workshop focused on the *Rate of energy increase during peak power demand* as this is their priority management issue.

The resultant 22 BBN diagrams were simple structures (Figure 3) that generally adhered to the developmental guidelines outlined by Marcot et al., (2006). Predominantly, the BBNs were symmetrical (10 out of 22) or near-symmetrical (seven out of 22), limited to three

parent nodes per child node (some had four) and contained no more than four layers (three hierarchical levels). While most of the BBNs were relatively simple, more complex BBNs were developed for emergency management (Figure 4).

For the four cross-sectoral workshops, follow-up meetings and email discussions were used to populate the CPTs and collect narratives. Of the 56 stakeholders involved in the cross-sectoral workshops, 75% (42 out of 56) contributed to the CPTs. The main reason for stakeholders not contributing to the CPTs post-workshop was a lack of response to requests for follow-up meetings (11%). CPTs for the two sector-specific workshops were populated during the workshop itself following the development of the BBN structure diagrams.

4   Two examples for closer inspection

Two case study BBNs are presented here for detailed inspection regarding their development and outcomes. We highlight lessons learnt about BBN processes in this context of the outcomes generated by the workshops focusing on emergency management and planning.

4.1   Emergency management

The BBN developed for emergency management (Figure 4) was the most complex model developed by the stakeholders in terms of number of variables (29) and hierarchical levels (three). Four stakeholders, representing local and state Queensland Government agencies, were involved in developing this BBN.

The *Capacity of emergency management* was selected by the stakeholders as the indicator of adaptive capacity. This BBN was notable for including four parent nodes for the response variable rather than the recommended three. Furthermore, these were each discretized to three levels (high / medium / low) rather than the recommended two levels. The stakeholders highlighted that the use of four nodes at the first hierarchical level was consistent with the

emergency management framework implemented in Queensland (Preparation / Planning / Response / Recovery) and therefore was supported by the researchers. With the agreement of all four stakeholders, the number of levels assigned to the primary nodes was decreased from three levels to two (high / low) to reduce the size of the associated CPTs. This adjustment represented the only change made to the BBN structure diagram in progressing it into a functioning BBN. The number of nodes assigned to subsequent hierarchical levels varied between one and three and all were discretized to two levels.

Given the complexity of this BBN, the individual CPTs were broadly similar across the four stakeholders, with some exceptions. There was clear divergence in the CPTs regarding the level of influence that *Capacity to respond*, *Funding* (for preparation), *Degree of success* and '*Recency' of disasters* had on their respective child nodes.

The results of the sensitivity analysis (Table S2 - supplementary material) indicated that the *Capacity of emergency management* was most sensitive to *Capacity to respond* and *Level of preparation* at the first hierarchical level. At this level, follow up conversations noted that a catastrophic event would overwhelm level of preparation. Furthermore, participants felt that 'preparation' was where they were held accountable. From the narrative capture, one participant highlighted a paradox concerning the relationship between the *Degree of success/failure* (of previous emergency management situations) and how it related to the amount of *Funding* that was obtained for *Level of preparation*. Failure of emergency management to 'cope with previous emergency situations' was linked to subsequent increased funding and subsequently improved preparation, with the example given being post event funding as a result of the 2009 Victorian bushfires in Australia (Victorian Bushfires Royal Commission, 2009). However, this perception was at odds with the perceptions of the other three stakeholders, who believed that increased funding was linked to success rather than failure.

At the second hierarchical level, the response variable was sensitive to the *Level of skill in response workforce*, while at the third hierarchical level, *Trainer competence* was the most influential variable. Both of these are ancestor nodes for *Capacity to respond,* indicating that they are influential determinants of this adaptive capacity indicator as perceived by all the stakeholders.

The response variable was also sensitive to the *Level of resilience of infrastructure* at the second hierarchical level and therefore appears to be an important determinant. This is despite this variable being a parent node for *Degree of prevention*, which was only the third most influential variable at the first hierarchical level. This occurs because *Level of resilience of infrastructure* is the sole parent node for *Degree of prevention* and therefore the latter is only dependent on (or sensitive to) the former.

The least sensitive node of the combined model was *Degree of success*, although the narratives of two of the stakeholders, when populating the CPTs, indicated that this was actually perceived as a critical determinant of the *Level of preparation (*through *Funding*.

4.2   Planning

The planning sector selected *Biodiversity* as their priority issue. This group comprised five stakeholders, four were local council officers from the same department and one person was from an NGO. One stakeholder was not available for the CPT step of the process.

This example is included because the development of the BBN structure diagram and its parameterization was not as straightforward as it was for the others. Key issues with the initial BBN structure diagram (Figure 5) included too many nodes at the second hierarchical level and many nodes discretized to three or four levels. Both issues presented a considerable

challenge to populating the CPTs through expert opinion (Kjaerulff and Madsen, 2008; Shaw et al., 2010).

The follow-up discussions with the stakeholders initially sought to address the issues of too many nodes and discretized levels. Initially, effort was towards reducing the number of nodes to a more tractable level. This resulted in a symmetrical BBN structure with three parent nodes at each hierarchical level (Figure 6). With the agreement of stakeholders, this was achieved by grouping *Funding* and *Capacity* as a single variable, and nesting *Pest* within *Knowledge of issues,* and removal of *Scale of connectivity* as a variable.

The stakeholders then reduced the number of discretized levels to a maximum of two and took the opportunity to provide more descriptive states to many of the variables. These descriptive states were based on definitions stipulated in legislation, such as the *Vegetation Management Act 1999* and the Queensland BioCondition assessment guide (Eyre et al., 2011). For example, the states for *Extent* (of the protected area) were changed from *Large* and *Small* to *>30% Remnant vegetation cover* and *≤30% Remnant vegetation cover*.

The results of the sensitivity analysis are summarized in Table S3 (supplementary material). At the first hierarchical level, the results indicate that the most sensitive response variable was *Extent*, followed by *Connectivity* (between biological communities) and *Condition* (of biological community). Biodiversity was also sensitive to *Funding* and *Availability of land* at the second level, with both acting through *Extent*. There was consensus between the stakeholders regarding the importance and relative influence of *Extent* on *Biodiversity*. However, at the second hierarchical level, there was divergence regarding the importance of *Availability of land* and *Funding* as a determinant of *Extent*. Two stakeholders strongly believed that *Availability of land* was more important than *Funding* as a determinant of

Extent, while one stakeholder believed the opposite was the case. The fourth stakeholder stated that they were unable to assign states for this particular CPT.

5   Discussion

The systems conceptualization served its intended purpose to prime participants for the construction of BBNs.

From a cross-sectoral perspective, what emerged from our study are questions about the determinants of, or influences on, adaptive capacity. For example, it would be tempting to conclude that factors such as adequate funding and proactive policy are generic and fundamentally critical, and there are elements of convergence and divergence in the adaptive capacity indicators (priority issues expressed as variables) across the four settlement types.

In the two cases discussed, the initial choice of a central priority issue had some bearing on how smoothly it was deconstructed. The structure of the BBN for *Biodiversity* (planning case study) proved to be a difficult construct because at the first level, the workshop participants chose three biophysical attributes of ecosystems and no socio-political attributes, and this appeared to have ramifications for subsequent levels of the BBN.

In contrast, the priority issue chosen by emergency management (*Capacity of emergency management*) more readily enabled the identification of clear states at the first level (effective/ineffective). There was rapid consensus that the most important variables influencing this priority issues could be captured under the variables of *Level of preparation, Degree of preparation, Capacity to respond,* and *Recovery capacity.* These four variables conform with well-established foundations for strategic planning for, and responding to, disasters. The narratives of individual members of the group clarify the rationale for the variable '*Capacity to respond'* and the context influencing its attributed significance, often through comparisons.

The two cases showed how professional/organizational cultures affect group dynamics and decision-making. Emergency management professionals are trained to make decisive decisions about priorities because they cannot rely on negotiated process in the midst of emergencies. However, planners have different processes for setting priorities and making decisions, and rely heavily on negotiated priorities and outcomes.

Comparisons of the conditional probabilities of the two case studies highlighted a mixture of divergent and convergent beliefs between individual group members. This was reflected in the sensitivity analysis of the BBNs, highlighting that the sensitivity of variables to direct descendant nodes was not always perceived consistently between group members. Often the accompanying narrative provided important contextual information that explained the observed differences. This highlights the importance of supporting the mechanistic nature of the modeling processes with follow-up interviews if models are to accurately reflect the expert opinion from which they are derived.

While most of the BBNs were relatively simple, more complex BBNs were developed in the case of emergency management (Figure 5). This reflects the hierarchical, top-down governance structures within the emergency management sector (structured around preparation, prevention, response and recovery) as well as an organizational mindset well aligned with the hierarchical structures of BBN.

Consensus, with some exceptions (e.g. *Capacity to respond*, *Funding for preparation*, *Degree of success* and '*Recency' of disasters*), was also evident from the workshop and the follow-up meetings with emergency services managers in regards to the conditional probabilities that were assigned. For example, there was clear divergence in the CPTs regarding the level of influence that had on their respective child nodes. This may reflect a combination of the

professional culture encouraged among emergency management personnel and significant experience in the field.

The BBN developed for the planning sector (Figures 5 and 6) involved many of the states being changed from broad qualitative descriptions to more refined, semi-quantitative descriptions through post-workshop interviews. The group processes in constructing the BBN did not flow as smoothly as the emergency management group, because variables identified did not lend themselves to hierarchical modeling and the professional culture of the planners involved greater divergence in thinking and experience. The participants felt that the follow-up interviews helped them better understand the interactions of the variables and made it easier to assign the conditional probabilities. This updating and refining of a BBN is an important part of the model development process, although in this instance, this was primarily motivated by the need to address problems in the original BBN structure diagram.

Sensitivity analyses applied to the BBNs helped identify the key determinants of the priority issues. In the context of the focus on climate change adaptation, they were used to help identify the important leverage variables within the identified system. However, two issues emerged that researchers need to be aware of when reviewing the results of sensitivity analyses: (1) the effect of asymmetric BBN structures; and (2) the effect of using CPTs elicited from multiple experts.

The results of sensitivity analyses need to be viewed carefully when applied to asymmetric BBNs (Marcot et al., 2006) as they can lead to misleading sensitivity results and consequently erroneous judgements. This was exemplified in the sensitivity analysis for the emergency management BBN (Table S2), where the results highlighted a significant causal pathway through the following sequence of variables: *Funding - Level of resilience of infrastructure - Degree of prevention - Capacity of emergency management*. The main issue

is that *Funding* is the sole parent node for *Level of resilience*, which in turn is the sole parent node for *Degree of prevention*. Therefore, there is a strong level of dependence (dictated by the associated CPTs) along this pathway. However, the stakeholders clearly identified during the workshop and post-workshop meetings that *Degree of prevention* was not an important determinant of *Capacity of emergency management* and therefore the influence of this causal pathway is misleading. To address this, the sensitivity analysis could be repeated with these single node pathways omitted (*Netica* has the capability of non-selection of specified nodes for the sensitivity analysis process).

Of the 22 BBNs developed in this study, 45% were symmetrical and therefore this 'asymmetric effect' was not an issue. Seven BBNs (32%) were symmetrical to within one variable (see Figure 3), and in these instances, asymmetric issues should be minor. Of the remaining five BBNs, the asymmetric effect is likely to be more important, as exemplified by the emergency management example, and needs to be considered when evaluating the results of associated sensitivity analyses.

The sensitivity analysis was also influenced by the use of CPTs populated by multiple experts. Divergence in probabilities can occur when using expert elicitation and auxiliary variables (equally weighting each of the stakeholder probabilities) provide a formal framework for these differences (Kjaerulff and Madsen, 2008). However, even using auxiliary variables, divergence between probabilities can enhance or attenuate the level of influence that a parent node has on a child node. This was exemplified in the results of the sensitivity analysis carried out on the emergency management BBN (Table S2 - supplementary material). The least sensitive node was the *Degree of success,* even though, independently (through elicitation of expert opinion via the CPTs), the stakeholders considered this an important determinant of *Funding* and subsequently *Level of preparation*. The associated individual CPTs and the accompanying narrative provided the evidence as to

why there was inconsistency between this seemingly shared belief and the results of the sensitivity analysis. This was due to divergence of opinion in how this variable was important and therefore the significance ascribed to it in CPT construction, rather than whether it was important. Three of the stakeholders indicated that *Funding* depended positively on the degree of success (more success, more funding). However, the fourth stakeholder strongly believed that *Funding* depended negatively on success, stating that failure was more likely to stimulate funding (for preparation) than success, and this belief was manifested clearly in the stakeholder's CPT. Consequently, the effect of this divergence on the group-averaged CPT was for the size of the influence to be dampened. The presence of such conflicting narratives can help highlight areas of common and uncommon understanding (Henriksen et al., 2006) and provide focus for further discussions (Hukkinen, 1991) and model adjustment.

In addition to contextualising the sensitivity analysis results, the accompanying narrative recorded during the expert elicitation of the conditional probabilities proved to be an important part of the overall BBN model development process. It assisted in identifying why stakeholders selected a specific priority issue and the associated causal nodes, how discretization states and conditional probabilities were selected, as well as providing important background information for their sector.

It was also apparent that effective facilitation and communication with the stakeholders was a critical element of the BBN development process. This is important when dealing with contentious issues (Bromley et al., 2005) and avoiding the influence of linguistic uncertainty on expert elicitation (Regan et al., 2002). Many of the workshop stakeholders were unfamiliar with BBN modeling or its associated terminology such as 'states' and 'variables'. Therefore, emphasis was placed on providing background information about BBNs to the stakeholders at the beginning of each workshop. The importance of having at least one researcher per group to guide the development of the BBN structure diagram also became apparent during the

workshops. Similarly, the follow-up meetings provided a critical forum for feedback about the BBN development process, including the robustness of the methodology. For example, a recurring comment was that BBNs were subjective and therefore biased towards their personal beliefs. On this matter, it was re-iterated to the stakeholders that the model was indeed subjective and that the BBN framework was suitable for developing the model based on their belief system and expertise through the concept of expert opinion (Castelletti and Soncini-Sessa, 2007).

Ongoing review and refinement of any BBN is an important part of its development process (Marcot et al., 2001, 2006), although the limited availability of resources that typically constrain research (especially the availability of time and funding for researchers and stakeholders) can restrict the level of review and refinement that actually occurs. Resource availability was an important constraint in our research and was instrumental in limiting the models to alpha-level BBNs. Nevertheless, the primary objective of this research was fulfilled through the development of 22 BBNs that were coherent, meaningful and that broadly adhered to BBN development guidelines (Marcot et al., 2006). However, the results presented for the planning sector did highlight the utility of being able to update the model. In this example, shortcomings in the initial BBN structure (too many parent nodes) and discretized levels (too many levels) provided the motivation for revisiting the BBN after the workshop. Without changes, expert elicitation of the complex CPTs that would have resulted from the combination of a high number of nodes and states would have been difficult and time consuming to complete (Hosack et al., 2008; Shaw et al., 2010). Rather, the result was a revised model structure that included a reduced level of, but more explicitly defined, variable states.

The BBNs have not been validated. The omission of a validation step is often cited as a shortcoming in BBN development (Marcot et al., 2006; Howes et al., 2009), although this

typically happens after the models have been formally peer-reviewed (beta-level model). There is also the challenge of how to validate BBNs that have been populated with qualitative socio-economic variables. In the absence of data, and reliance on expert opinion, the BBN could be validated using an independent set of experts (Marcot et al., 2001). However, this is not a suitable approach here because this project is focused on making the subjective judgements of the stakeholders involved in the workshops explicit. These stakeholders make decisions that are based on their personal or collective professional mental models (social representations) of what are the determinants of adaptive capacity and the relative influence of the various determinants. Making this explicit forces stakeholders to consider their personal and collective biases and understandings when making decisions and could precipitate 'research' or validation of the assumptions inherent in their decision-making.

6   Conclusion

This project aimed to identify the perceived determinants of adaptive capacity, upon which stakeholders are acting. A combination of system conceptualization and BBN modeling was used to identify these perceived adaptation pathways within complex, socio-ecological systems where opinion and judgment are linked in determining the adaptive capacity of human systems to climate change. Overall, the sequential modeling approach provided a mechanism for exploring this pragmatic level of understanding of, and its relationship to, adaptive capacity to climate change as understood by the stakeholders involved in this study.

Commonly identified (generic) determinants included in the BBNs, such as funding and levels of awareness, had the greatest level of contention about their relative importance, while the more numerous pragmatic, context based determinants of adaptive capacity appeared to gain consensus. That is, while generic determinants existed, their influence was moderated by

sector-specific issues. Drawing out these sector-specific determents is of value to stakeholders because it empowers them to articulate and share their grounded knowledge.

An important lesson that emerged from this study, and one with implications for similar modeling studies, is that the mechanistic nature of model building can hide meaning, at least, when uncertainty is high and consensus is low. Under these circumstances, accompanying narrative capture becomes an important component of the model building process.

Furthermore, these types of models should be progressed by taking findings back to stakeholder groups for further consideration and adjustment as part of a learning process rather than simply an exercise in model building. Alternatively, reconsideration can focus on building BBNs for sectors with specific responsibilities and influences to focus their adaptation strategies after being made aware of broader intersectoral issues and priorities through the initial systems thinking process. While modeling techniques are increasingly being used interactively with stakeholders to address the emerging multi-disciplinary nature of global change modeling, it is clear from this study that these techniques have both limitations (e.g. divergent beliefs) and advantages (e.g. participatory model building) of which the researchers employing them should be aware.

Sunshine Coast and University of Queensland. The Initiative aims to provide research

knowledge to enable the region to adapt and prepare for the impacts of climate change.

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Table 1. Priority Issues selected by the workshop stakeholders.

Sector	Region	Priority issue (desirable state / undesirable state)	n
Coastal management	Gold Coast	Currently built infrastructure (good condition / poor condition)	2
	Moreton Bay	Coastal erosion (manageable / unmanageable)	2
	Sunshine Coast	Vulnerability of built environment to climate change (low / high)	3
Emergency management	Gold Coast	Capacity of emergency management (effective / ineffective)	4
	Ipswich	Vulnerable groups (empowered / disempowered)	2
	Moreton Bay	Community resilience and capacity (self-recovery / aided-recovery)	4
	Sunshine Coast	Community resilience (high resilience / low resilience)	3
Health	Gold Coast	Health (equitable / not equitable)	2
	Ipswich	Health - well being (well / unwell)	2
	Moreton Bay	Health	3

Sector	Region	Priority issue (desirable state / undesirable state)	n
		(well / unwell)	
Infrastructure	Sunshine Coast	Capacity to manage health effects (adequate / inadequate)	2
	Gold Coast	Government policy on climate change (supported / not supported)	3
	Ipswich	Community well-being (high level/ low level)	3
	Moreton Bay	Infrastructure design (climate resilient / not climate resilient)	3
	Sunshine Coast	Economics of infrastructure (money [funded] / no money [not funded])	2
Planning	Gold Coast	Biodiversity (loss / no loss)	5
	Ipswich	Planning (coordinated / uncoordinated)	3
	Moreton Bay	Settlement pattern (affordable living / unaffordable living)	2
	Sunshine Coast	Planning (sustainable / unsustainable)	5
Biodiversity	SEQ	Functionality of ecosystems	3

Sector	Region	Priority issue (desirable state / undesirable state)	n
		(healthy / unhealthy)	
		Impact of development on marine and coastal areas	3
		(low / high)	
Energy	SEQ	Rate of increase - peak power demand	4
		(manageable / unmanageable)	

List of Figures

Figure 1. Conceptualization of a single level BBN structure diagram developed around a selected priority issue by workshop participants.
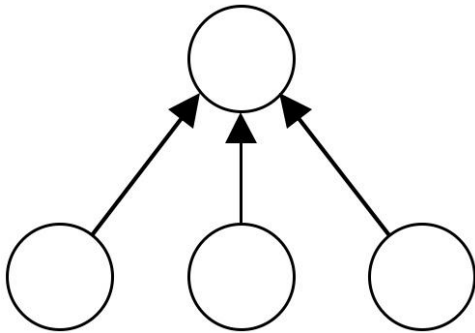

Figure 2. Conceptualization of a two-level BBN structure diagram developed around a selected priority issue by workshop participants.
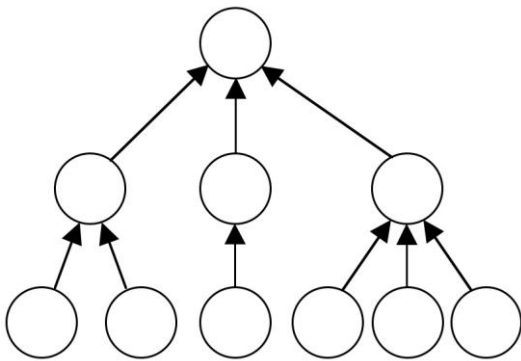

Figure 3. Example BBN structures developed during the stakeholder workshops that were symmetrical to within one variable.
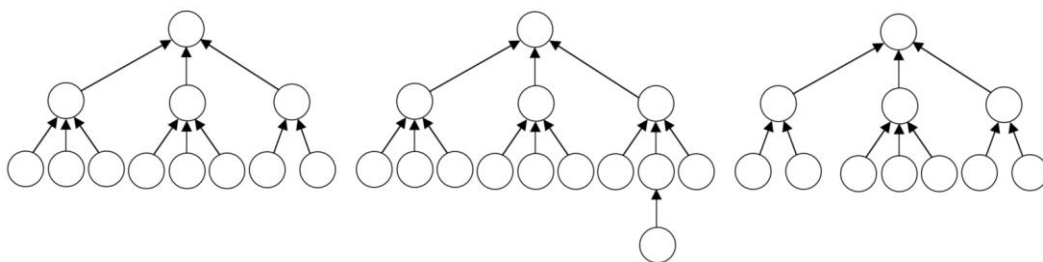
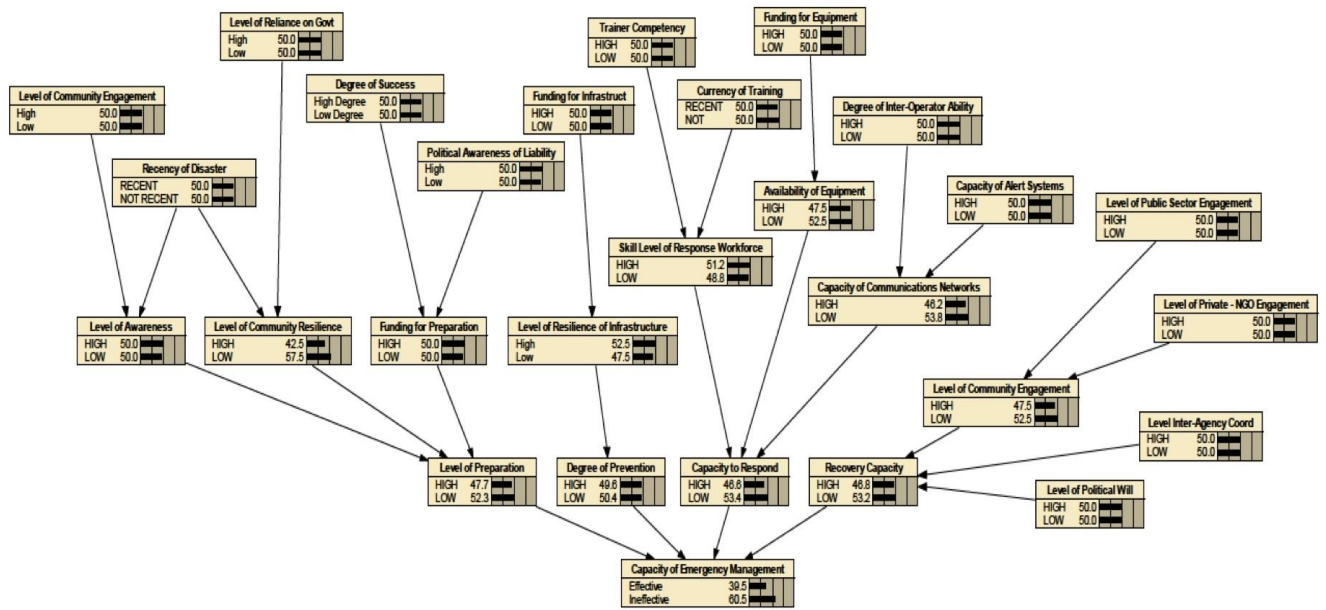**Figure 4. BBN for the Emergency Management case study.**

Figure 5. Initial BBN structure for the Planning case study. This structure contains five parent nodes for *Condition* and four parent nodes for *Connectivity*.
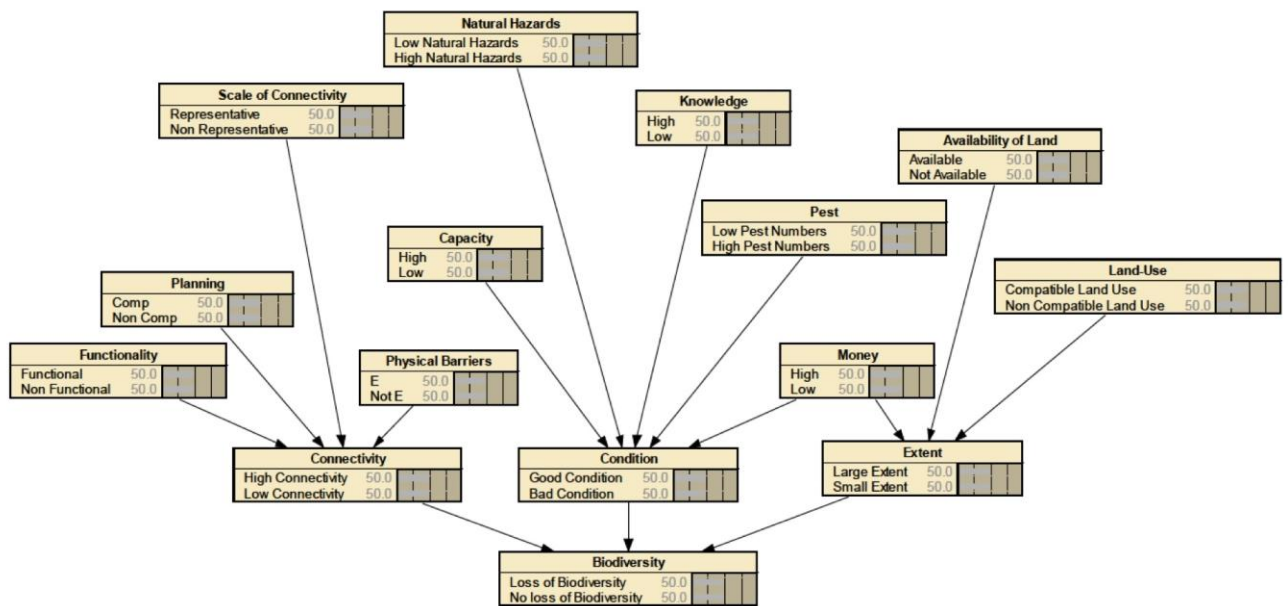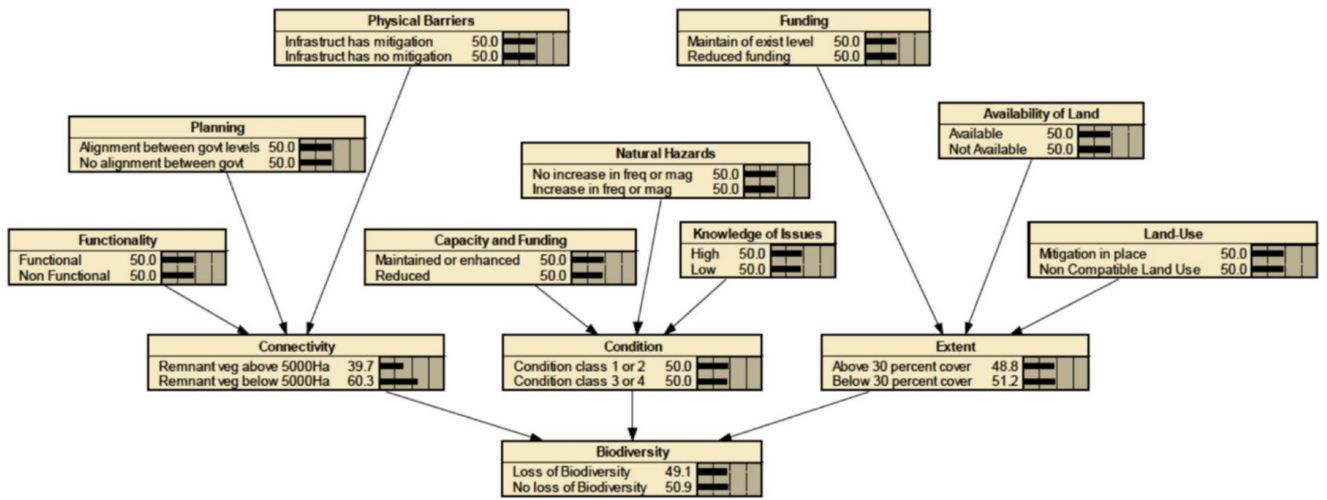
Figure 6. Updated BBN following post-workshop discussions with the stakeholders.

Appendix A. Supplementary material

Sector	Region	Priority issue (desirable state / undesirable state)	n
Coastal management	Gold Coast	Currently built infrastructure (good condition / poor condition)	2
	Moreton Bay	Coastal erosion (manageable / unmanageable)	2
	Sunshine Coast	Vulnerability of built environment to climate change (low / high)	3
Emergency management	Gold Coast	Capacity of emergency management (effective / ineffective)	4
	Ipswich	Vulnerable groups (empowered / disempowered)	2
	Moreton Bay	Community resilience and capacity (self-recovery / aided-recovery)	4
	Sunshine Coast	Community resilience (high resilience / low resilience)	3
Health	Gold Coast	Health (equitable / not equitable)	2
	Ipswich	Health - well being (well / unwell)	2
	Moreton Bay	Health (well / unwell)	3
	Sunshine	Capacity to manage health effects	2

Sector	Region	Priority issue (desirable state / undesirable state)	n
Infrastructure	Coast	(adequate / inadequate)	
	Gold Coast	Government policy on climate change (supported / not supported)	3
	Ipswich	Community well-being (high level/ low level)	3
	Moreton Bay	Infrastructure design (climate resilient / not climate resilient)	3
	Sunshine Coast	Economics of infrastructure (money [funded] / no money [not funded])	2
Planning	Gold Coast	Biodiversity (loss / no loss)	5
	Ipswich	Planning (coordinated / uncoordinated)	3
	Moreton Bay	Settlement pattern (affordable living / unaffordable living)	2
	Sunshine Coast	Planning (sustainable / unsustainable)	5
Biodiversity	SEQ	Functionality of ecosystems (healthy / unhealthy)	3
		Impact of development on marine and	3

Sector	Region	Priority issue (desirable state / undesirable state)	n
		coastal areas (low / high)	
Energy	SEQ	Rate of increase - peak power demand (manageable / unmanageable)	4