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REVIEW

Mental models for conservation research and practice

Katie Moon[1] | Angela M. Guerrero[2] | Vanessa. M. Adams[3] | Duan Biggs[2,4,5] | Deborah A. Blackman[1] | Luke Craven[1] | Helen Dickinson[1] | Helen Ross[6]

[1] Public Service Research Group, School of Business, University of New South Wales, Canberra, Australian Capital Territory, Australia

[2] Centre for Biodiversity & Conservation Science, School of Biological Sciences, The University of Queensland, Brisbane, Queensland, Australia

[3] School of Technology, Environments & Design, University of Tasmania, Hobart, Tasmania, Australia

[4] Environmental Futures Research Institute, Griffith University, Nathan, Queensland, Australia

[5] Department of Conservation Ecology and Entomology, Stellenbosch University, Matieland, South Africa

[6] School of Agriculture and Food Sciences, The University of Queensland, St Lucia, Brisbane, Australia

Correspondence
Katie Moon, Public Service Research Group, School of Business, University of New South Wales, Canberra, ACT, 2601, Australia.
Email: katieamoon@gmail.com

Abstract

Conservation practice requires an understanding of complex social-ecological processes of a system and the different meanings and values that people attach to them. Mental models research offers a suite of methods that can be used to reveal these understandings and how they might affect conservation outcomes. Mental models are representations in people's minds of how parts of the world work. We seek to demonstrate their value to conservation and assist practitioners and researchers in navigating the choices of methods available to elicit them. We begin by explaining some of the dominant applications of mental models in conservation: revealing individual assumptions about a system, developing a stakeholder-based model of the system, and creating a shared pathway to conservation. We then provide a framework to "walk through" the stepwise decisions in mental models research, with a focus on diagram-based methods. Finally, we discuss some of the limitations of mental models research and application that are important to consider. This work extends the use of mental models research in improving our ability to understand social-ecological systems, creating a powerful set of tools to inform and shape conservation initiatives.

KEYWORDS

Bayesian belief networks, cognitive maps, decision-making, influence diagrams, modeling, perceptions, pragmatism, qualitative, social science, social-ecological system

1 | INTRODUCTION

Conservation is an action-oriented field focused on reimagining the future as "a world where people understand, value, and conserve the diversity of life on Earth" (SCB, 2016). Yet, conservation takes place in complex social-ecological systems, thus requiring an understanding of the complex biophysical and social processes of the system, as well as the different meanings and values that people attach to them (e.g., Ban, Mills, & Tam, 2013). Successful conservation therefore relies on the codesign of policies, strategies, and programs that meet multiple objectives and diverse needs and priorities (e.g., Blomkamp, 2018, Nel et al., 2016). Mental models research offers a useful set of methods to elicit and share complex knowledge structures and reveal assumptions that influence support for when, why, and how species and ecosystems should be conserved (e.g., Game, Meijaard, Sheil, & McDonald-Madden, 2014).

A mental model exists in someone's mind as a small-scale model of how (a part of) the world works. When elicited, they represent how individuals structure and organize concepts cognitively, revealing understandings of dynamic and interconnected elements of social-ecological systems (Jones, Ross, Lynam, Perez, & Leitch, 2011). Mental models are based on a person's knowledge, experience, values, beliefs, and aspirations, explaining how they reason, make decisions, behave, and selectively filter and interpret information (Easterby-Smith, 1980). Mental models are functional, but incomplete representations of "reality" that are context dependent and change over time through learning (Jones et al., 2011; Pearson & Moon, 2014). Strictly speaking, mental models are unique to their individual holders because no two minds are alike, but aspects can be shared (Jones, Ross, Lynam, & Perez, 2014, Lynam et al., 2012). Examples of shared mental models include cultural understandings of the world (Jones et al., 2011) and views about a particular topic or problem (Eden & Ackerman, 1998).

An ongoing challenge with mental models research is that it is difficult to decide which method is the most appropriate for a given context and why. Several methods are available to elicit mental models, namely interviews (Morgan, Fischoff, Bostrom, & Atman, 2002), drawings (Jones et al., 2014), repertory grids (Kelly, 1955), and a variety of mapping techniques including influence diagrams (Diffenbach, 1982), cognitive maps (Axelrod 1976), fuzzy cognitive maps (Özesmi & Özesmi, 2004), and Bayesian belief networks (BBN) (e.g., Pollino, Woodberry, Nicholson, Korb, & Hart, 2007). Depending on the application, some elicitation and analysis methods will be more suitable than others, yet the literature provides little guidance in how to navigate among the choices (see Jones et al., 2014).

Our paper aims to assist researchers and practitioners to navigate the choices available in mental models research methods. The paper is structured into three sections. The first section explores some of the dominant applications, and thus value of mental models for conservation research and practice. The second section provides a "walk through" of the stepwise decisions that can be useful when engaging in mental models research, with a focus on diagram-based methods. We present a framework to assist in this "walk through," which adopts a pragmatist perspective. This perspective focuses on the most appropriate strategies to understand and resolve problems, rather than holding to a firm philosophical position (e.g., Sil & Katzenstein, 2010). The third section discusses some of the limitations of mental models research and application.

2 | THE ROLE FOR MENTAL MODELS IN CONSERVATION

Mental models can assist conservation in a number of ways. They can reveal how people understand the system, in terms of its content (what exists in the system) and structure (how the parts of the system are arranged or how they function). They can also provide opportunities to create a conceptual model of a system on the basis of the collective knowledge of a group of stakeholders (e.g., Colvin, Witt, & Lacey, 2016), which can underpin mathematical modeling. Models can also be elicited in a group setting to create a shared vision for how people would like to experience or change a system. We explore each of these main applications in turn, with specific reference to diagram-based methods.

We focus on diagram-based methods because they enable abstraction, a process that allows the complexity of a system to be reduced to an appropriate level of simplicity by focusing on only the most relevant aspects, to which layers of complexity can be added (Anderson, Meyer, & Olivier 2002). One of the most common diagram-based methods used to capture relationships between variables within a social-ecological system is directed graphs, or digraphs. Digraphs have a foundation in graph theory, which offers theory and methods for comparison and application of models (see Biggs, Lloyd, & Wilson, 1976). Digraphs comprise variables connected by lines with arrowheads (directional relationships) that indicate which variable is perceived to have an effect on other variable(s) (see Figure 1 for an example). Digraphs can be used, for example, to show causal relationship among variables described by people to create "cognitive maps" (e.g., Axelrod, 1976), or they can be used in conjunction with systems dynamics modeling to create "influence diagrams" (e.g., Diffenbach, 1982). One of the main advantages of diagrammatic models is that they can elicit more stable, rather than situation-dependent, knowledge (Cooke, Salas, Cannon-Bowers, & Stout, 2000).

2.1 | Revealing individual assumptions about a system

Eliciting individual mental models can allow researchers, research participants, and practitioners to identify how people construct their own model of a system (Figure 1). For example, Moon and Adams (2016) engaged a number of practitioners involved in cross-agency management of an invasive species. They asked participants to model the system from *their* perspective in terms of (1) who *should* be responsible for managing invasive species, (2) how they *should* manage invasive species, and (3) for what outcomes. They elicited models from 15 individuals across five agencies to identify the interrelationships that defined the system, which revealed the dominant problems that practitioners perceived were limiting effective action.

Eliciting individual mental models can be particularly useful in making explicit the implicit assumptions individuals make or hold, and how it affects their understanding of a system (Moon, Blackman, Adams, & Kool, 2017). Revealing connections between assumptions, preferences, and

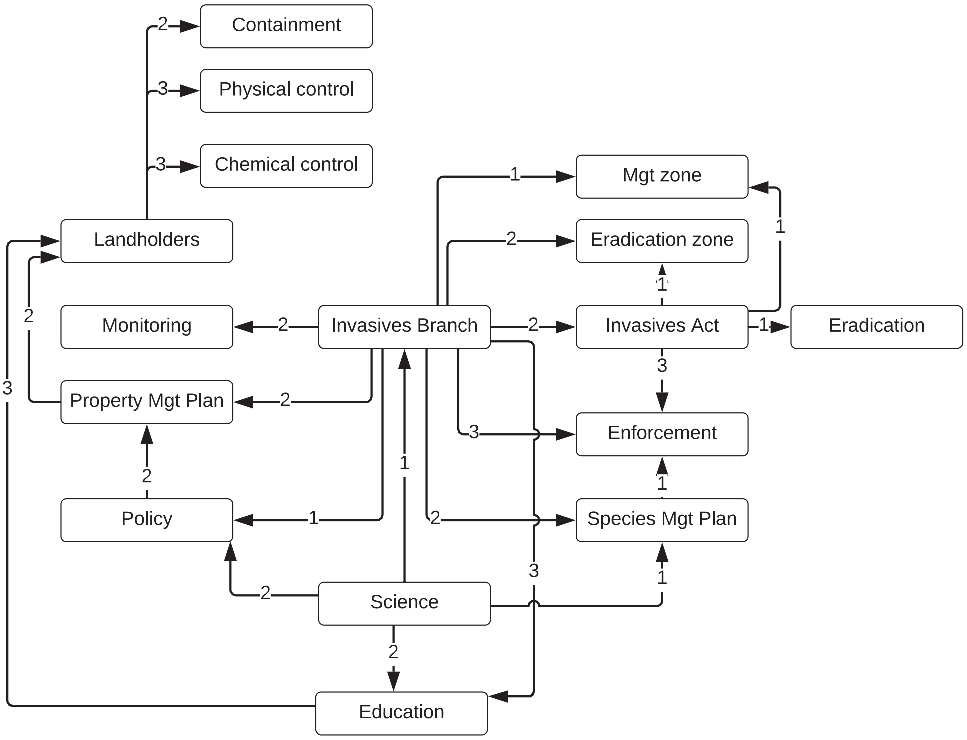

FIGURE 1 Example of a digraph representation of a mental model of invasive species management elicited through influence diagram method. Arrow heads represent the direction of the influence; numbers (1—weak, 2—moderate, 3—strong) represent the strength of the influence (adapted from Moon & Adams, 2016)

knowledge makes it possible to understand why individuals have particular points of view, how they make decisions, and how conflict might arise (e.g., Axelrod 1976). In these applications, mental models can enable sharing of knowledge, correct misconceptions, permit solutions to be negotiated, and aid in conflict resolution by providing people with an opportunity to share their point of view on the basis of their own knowledge and experiences (e.g., Halbrendt et al., 2014; Robertson & Hull, 2001).

To illustrate the value of mental models in revealing the role of assumptions, El Sawah, Mclucas, and Mazanov (2013) interviewed a group of water users to identify how they understood drivers of water availability and how such drivers should be managed. The authors found two contrasting ways in which participants framed water issues: one group viewed water management as a technical problem, where high investments in infrastructure were perceived as the only solution; another group viewed excessive water use and population growth as dominant drivers, where water-efficient technologies were seen as the solution. This research revealed the need for communication strategies that responded to the conflict between the two problem framings and dominant misconceptions about the system.

Individual mental models can also be used to identify and explore potential unintended consequences of conservation interventions (Larrosa, Carrasco, & Milner-Gulland, 2016). For example, Guerrero, Jones, Biggs, and Ross (2018) interviewed people involved in the production and trading of soybeans to understand enablers, barriers, and solutions within their mental models of deforestation-free soy supply chains. The findings revealed some farmers perceived that policies would threaten their land use rights, and some who were previously conserving (i.e., putting aside native habitat) were now considering clearing this land, exercising their rights in the event they were "taken away" if deforestation-free policies came into place. In this type of application, mental models were used to understand the factors that supported or disabled conservation behavior, and thus identified possible negative effects of proposed conservation policies *before* they were implemented.

Mental models can also be used to design interventions that provide for the diverse needs of local communities (Sandbrook, 2017), thereby increasing the suitability and success of interventions (Biggs et al., 2011; Etienne 2011). Mental models can be used to explore how people consider evidence should be integrated into conservation (Newton, Stewart, Diaz, Golicher, & Pullin, 2007), what factors influence land management decisions (Murray-Prior, 1998), how and why conservation practices are adopted (Prager & Curfs, 2016), how conservation is influenced by uncertain and complex social and political processes (Meliadou et al., 2012), and how people decide who should be involved in decision-making processes and why (Moon et al., 2017).

2.2 | Developing a stakeholder-based model of the system

To succeed, conservation interventions often need to change certain elements of social-ecological systems, such as managing threats to biodiversity, reducing habitat loss, or changing individual behaviors such as water and energy consumption (Ferraro & Pressey, 2015). To achieve such change, a sufficient understanding of a defined system is often necessary, which can be supported by developing models of that system (e.g., Law et al., 2017). This application of mental models fits with Rouse and Morris' (1986, p. 351) definition: "Mental models are the mechanisms whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future system states."

At a general level, developing stakeholder-based models of a system can be useful for coordinating actions in a team setting (e.g., Klimoski & Mohammed, 1994). Returning to the example outlined above, Moon and Adams (2016) identified significant positive correlations (i.e., shared aspects of mental models) between half of the participants, indicating that some participants had similar models that could be used as a starting point for developing a team model to clarify roles and responsibilities for ecosystem management. Participants identified a number of areas for improvement: better use of management tools, namely education and enforcement, better coordination and collaboration between agencies, and targeted resourcing.

At a more detailed level, stakeholder-based models of a system can be used as the basis for mapping system dynamics (El Sawah, Guillaume, Filatova, Rook, & Jakeman, 2015; Game et al., 2017). When mental models capture interpretations of system dynamics, they can be used in system modeling to test the likely effects of different policy or management options (e.g., Gray, Chan, Clark, & Jordan, 2012; Özesmi & Özesmi, 2004). For example, Gray et al. (2012) used fuzzy cognitive mapping (FCM) to elicit the mental models of different types of stakeholders, then combined them to create a theoretical model of a fishery that served to model "what if" scenarios to test how the fishery might change under different conditions. In another context, a group of stakeholders used FCM in a participatory setting to create a model of an ecological system that identified variables that could be used as monitoring indicators based on the how the variables in the FCM responded to different policy options (Game et al., 2017). Mental models of system complexity have also been integrated with quantitative approaches for the development of agent-based models to test management alternatives (El Sawah et al., 2015).

Stakeholder mental models can also be used to forecast future system states under alternative futures. This application relies on having an understanding of the system, including causal relationships between variables. Data, typically "scientific evidence," are necessary to develop these relationships but are often missing or incomplete and must, therefore, be complemented with expert elicitation of mental models of system relationships (Colvin et al., 2016; Morgan, 2014). Once a complete system model is constructed, it can be used to test the effects of different management choices (e.g., Gray et al., 2012). For example, to support the design of water management allocation policies in the Australian Northern Territory, research was conducted on the relationship between river flows and fish populations. The first step in this process was to build a conceptual model of fish abundance to flow and other physical and biological factors through expert workshops and consultation (Chan et al., 2012). Further quantification of relationships was completed based on other sources of evidence, such as field studies. The conceptual models were then developed into BBN to examine how water extraction scenarios were predicted to influence fish abundance (Chan et al., 2012). These models were further integrated into a management scenario evaluation tool to support participatory modeling and scenario evaluation and complex policy analysis (Pantus, Barton, Bradford, & Stroet, 2011; Stoeckl et al., 2013).

2.3 | Creating a shared pathway to conservation

Conservation can quickly emerge as conflict, which stems from different stakeholder perceptions and values about the need for and approaches to conservation (e.g., Biggs et al., 2011; Redpath et al., 2013). Mental models research can assist in the incremental progress toward a shared pathway for conservation. "Focusing on easy-to-reach intermediate targets may provide a basis for stakeholders to begin to work together. In working toward this first goal, there will be opportunities for shared learning. The process will build the confidence and the trust needed to address further issues" (Sayer, et al., 2013, p. 8351). Mental models can be elicited and shared among stakeholders, facilitated through participatory and iterative processes that enable an understanding of each other's point of view and the discovery of areas of common ground (e.g., Abel, Ross, & Walker, 1998; Lynam et al., 2012; Özesmi & Özesmi, 2004). The progressive emergence of a shared vision can lead to a revision of assumptions (double-loop learning) and exploration of underlying values and beliefs (triple-loop learning) (e.g., Pahl-Wostl, 2009). Compared to individual and team elicitation methods, developing a shared mental model typically requires more money, time and facilitation or mediation skills, and demands a greater level of stakeholder participation (Halbe, Pahl-Wostl, & Adamowski, 2018).

A number of methods are available to support the development of a shared mental model. Examples of methods include participatory modeling (Voinov & Bousquet, 2010; Voinov, et al., 2018), role playing games (Pahl-Wostl & Hare, 2004), ARDI (Etienne, Du Toit, & Pollard, 2011), and group model building (Halbe et al., 2018). Methods can be used to identify the presence or absence of consensus (Biggs et al., 2008) or to seek to build consensus over time (Etienne et al., 2011). Shared vision planning (SVP) is an example of an integrative decision support tool that combines a number of methods to develop a comprehensive shared understanding of a system (Palmer, Cardwell, Lorie, & Werick, 2013). The tool includes a method called "circles of influence," which "organizes stakeholders or subsets of the interested public according to their interests and capability of understanding complex technical issues," drawing on specific individuals and groups as needed, and relying on social networks for the flow of information between "circles" (see Palmer et al., 2013, p. 619). SVP involves seven steps to develop and implement a plan and includes a "collaboratively built model" of the system. A team develops the model on the basis of the problems and objectives they identify, and then use the model to formulate and evaluate alternatives to the status quo, providing opportunities to select and implement a preferred alternative. The method has been used in a number of contexts, namely water management, but also climate change (see Palmer et al., 2013 for a review). Developing shared mental models as an iterative process provides opportunities for social learning (Biggs et al., 2011; Pahl-Wostl & Hare, 2004), which must then be supported by appropriate structures and processes that sustain this learning and enable joint action (Schusler, Decker, & Pfeffer, 2003).

Any attempt to develop a shared mental model must consider whether it is appropriate, or even possible, to create a meaningful shared model. We recognize that "multiple domains and types of knowledges, with different logics and epistemologies" exist (Agrawal, 1995, p. 433), creating the possibility that mental models could be commensurate or incommensurate with each other, or somewhere in between. For example, a mental model can only be "true" about its own specific objects that exist within a defined domain of knowledge or practice (Agazzi, 1985). Working toward an understanding of the commensurability of different mental models is an important part of creating a shared pathway to conservation.

3 | THE TYPE OF MENTAL MODEL NEEDED

The dominant applications of mental modes research discussed above provide a first step for determining what type of model might be best suited to assist with conservation policy and practice (Figure 2). Eliciting individual mental models reveals the structure and content of each person's individual model of a system. Individual mental models are those elicited from one person and are unique to them. Eliciting individual models is important for discovering the diversity of system understandings within a group of people. Moon and Adams (2016), for example, sought to elicit individual models to assist in understanding where the participants saw themselves in the system and why. The research showed that the centrality of the employing organization of the participant could influence their perceptions of how complex, (in)efficient, and malleable the system was. In other words, participants' mental models revealed how easy or difficult they perceived it would be to modify the system and how much power they had to influence the system. The authors used path length, among other measures, to draw these conclusions (see Moon & Adams, 2016 for further details).

Creating a team mental model can support the development of a stakeholder-based model of the system. Team mental models capture "the overall degree of similarity between the mental models of individual team members" (Langan-Fox, Wirth, Code, Langfield-Smith, & Wirth, 2001, p. 100). They can be generated from compiling the relationships among a group of elicited individual mental models into one model, or elicited as collective task and team-relevant knowledge. This latter application is defined in the organizational literature as "team situation models," which involves compiling a team's collective context-specific understanding of a defined situation or expectations and explanations for tasks (Cannon-Bowers, Salas, & Converse, 1993; Cooke et al., 2000). Team mental models reveal the dominant relationships and influences within the system as perceived by a set of individuals. Team mental models are commonly used to understand and model systems, but can also be helpful in understanding how sets of individuals make decisions and identify areas of agreement across individual mental models. These models can also be useful in clarifying whether or not individuals agree on their roles and responsibilities, and where major points of difference lie between models (Moon & Adams, 2016).

Eliciting shared mental models can assist in creating a shared pathway to conservation. "A shared mental model is the mental model constructed and shared when individuals interact together in a team setting, it represents the shared cognition among groups of individuals" (Jones et al., 2011, p. 4; Langan-Fox et al. 2001). They are often elicited over time, allowing individuals to discuss and agree on a representation of shared aspects of their individual models that can be used to assist in decision-making. Sharing mental models (including diverse perspectives and experiences) allows people to "develop a common framework of understanding and basis for joint action" (Schusler et al., 2003, p. 311), in other words, to co-create a mental model that is "held in common" (Biggs et al., 2011).

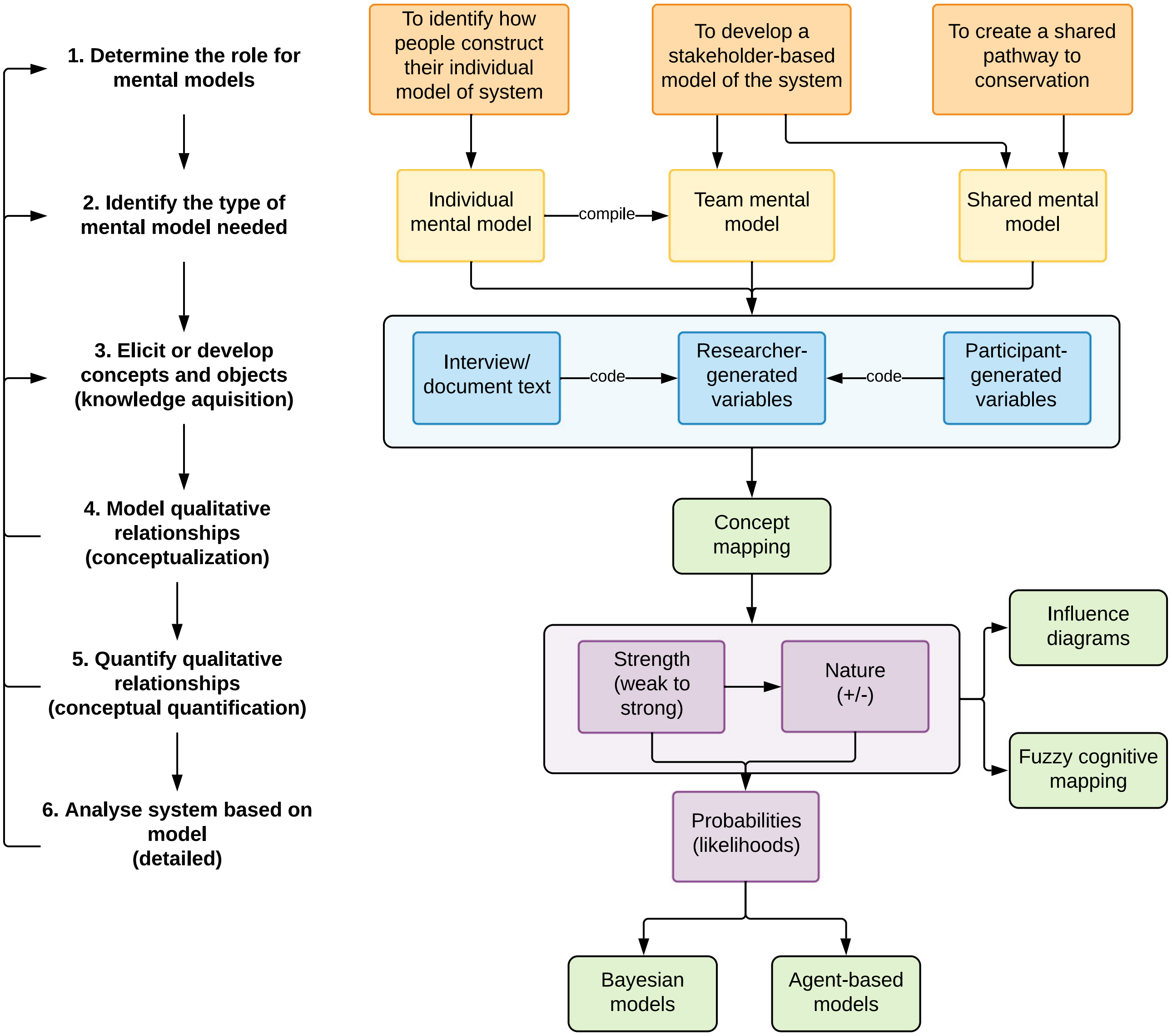

FIGURE 2 Framework outlining steps to consider in mental models research design. The process typically starts anywhere between Steps 1 and 3. Step 1 outlines three potential applications of mental models research for conservation. Step 2 shows the relationships between applications and dominant mental model types. Step 3 outlines the three most common methods for generating or eliciting concepts and objects to be used in diagrammatic mental model elicitation. Researchers or practitioners need to decide what type of data will be most helpful in eliciting the mental model (from interview text or from variables that are fully elicited from the participant, or preidentified by the researcher/s) depending on how the data will be used. Steps 4–6 have been partially adapted from Voinov et al. (2018). Step 4 involves positioning and connecting variables to define the structure of the model and usually involves drawing lines with arrowheads to connect two or more variables to one another (relationship). This step can be considered as a qualitative model of the relationships. Step 5 involves quantifying the qualitative relationships of the model. Simple quantification can involve defining the nature of the relationship (e.g., positive or negative) or the strength as weak, moderate or strong (e.g., influence diagrams). More detailed quantification can parameterize the relationship with a number between –1 (i.e., high negative influence) and 1 (i.e., high positive influence) at 0.1 intervals (e.g., fuzzy cognitive mapping). Step 6 involves modeling and testing the quantitative relationships, which can be done using probabilities of connections and causes (e.g., Bayesian and agent-based models)

4 | ELICITING OR DEVELOPING CONCEPTS AND OBJECTS

Once the type of model needed has been identified, the second step in eliciting a mental model as a digraph is to develop the concepts and objects as variables within a system (Cannon-Bowers et al., 1993). For example, in the case of invasive species management, the concepts and objects might relate to animal welfare, legislation, landholders, education, and control methods. The importance of concepts and objects to conservation policy and practice relates to *what* it is in the system that an individual includes in their model. For example, research shows that the brain does not attempt to provide a perfect simulation of the world, but rather an internal approximation that is individual, context-dependent, and typically developed on a needs-to-know basis (Yarbus, 1967). As a result, although people can think they "know" a system, specific questions about variables within that system can reveal differences or gaps in knowledge when those variables, and relationships between them, have not been previously relevant, observed, considered, or experienced by the individual. Thus, the content of a mental model can provide much insight into the knowledge and nature of experience of individuals.

Diagram-based mental model elicitation methods can use at least three main sources of information to create variables: interview or document text, participant-generated variables, and/or researcher-generated variables (Figure 2). Mental models can be elicited through open or semistructured mental models interviews (see Morgan et al., 2002) or laddering interview methods (see Reynolds & Gutman, 1988) that encourage participants to express mental models in their own terms. Alternatively, researchers can assist participants to elicit their mental models by asking them to develop or describe variables (e.g., words written on pieces of card) and explore or explain the connections between them. The participant defines their own variables (participant-generated variables) by describing them in their own way using their own terms with few cues or probes (e.g., Craven, 2017). These variables, and the links between them, can offer a useful approach to examine the overall diversity of understandings of a conservation problem or solution and the different causal assumptions, language, and meanings assigned to the variables within the system.

Researcher-generated variables are those developed *a priori* (e.g., from literature, or interviews) in a scoping phase, ensuring they are sensitive to context and relevant to the participants. They are provided to the participant to elicit their mental model (if any) about a defined topic (e.g., Moon & Adams, 2016; Pearson & Moon, 2014). This approach is particularly suited to comparisons and identification of similarities and differences between (sets of) individual mental models. Where necessary, statistical tests can be performed to identify significant differences between elicited mental models, including between groups of people (e.g., scientists and policy makers) (e.g., Moon et al., 2017). To increase the likelihood that participants are interpreting variables in a similar way, definitions of variables can be developed and provided to participants (e.g., Adams et al., 2018). Participants are typically invited to include any additional variables they consider essential to their model. Researcher-generated variables can also be synthesized from an analysis of participant mental models, using methods such as thematic or content analysis (e.g., Craven, 2017). Content analysis, for example, provides an opportunity to explore commonalities across participants' mental models. A researcher, could, for instance, examine a set of mental models and categorize areas of similar content.

5 | MODELING RELATIONSHIPS WITHIN MENTAL MODELS

The third step in eliciting a mental model as a digraph is to model the relationships between the concepts and objects. Modeling relationships within mental models can be performed in a number of complementary ways (e.g., Voinov et al., 2018). Here, we provide a brief overview of how relationships can be elicited in a way that adds increasing layers of complexity and understanding of a system. We first look at mapping qualitative relationships, then methods of quantifying those relationships and finally analyzing them.

5.1 | Mapping qualitative relationships

Relationships represent how a person considers that variables (i.e., concepts and objects) within a system relate to one another. To illustrate, drawing a single-headed or double-headed arrow between two or more variables is the first step in defining a "relationship" within a model. If the arrow points from variable A to variable B, it indicates that the individual(s) consider that variable A influences, or has a relationship with, variable B. Eliciting relationships within a person's mental model makes interrelationships between variables "more visible, more explicit, and thus more comprehensible," thereby improving the extent to which the effectiveness of different decisions can be assessed (Diffenbach, 1982, p. 133). These relationships can indicate which variables are highly influential in terms of enabling change or representing points of failure (Krebs, 2000). Of course, it is unlikely that mental models will be used alone to inform decisions, but they can become an important part of the evidence base that is used to make decisions and analyze options (Diffenbach, 1982).

5.2 | Quantifying qualitative relationships

Once a relationship has been defined, its nature can be recorded, permitting the researcher to integrate data on perceptions about the importance or strength of interactions influencing a system (e.g., Friedel, Grice, Marshall, & van Klinken, 2011) (Figure 2). This additional information can be particularly important in determining which variables are useful indicators of program success, thereby contributing to one of the "principal, and often most challenging, tasks of applied conservation science": monitoring (Game et al., 2017, p. 1).

Relationships can be described in general terms (e.g., influence diagrams) or in a more precise way (e.g., FCM). Qualitative influence diagrams can include simple descriptions of relationships, such as low (1), moderate (2), and high (3) influence of one variable or another (e.g., Moon & Adams, 2016). Further definition can be added by providing detail on the nature of the relationship, as either positive or negative (see Diffenbach, 1982). For example, if re-vegetation is perceived to have a strong positive influence on erosion control, it is represented as a line drawn with the arrow from the variable "re-vegetation" to the variable "erosion control" with a +3 symbol. FCM is a more descriptive form of cognitive map, using fuzzy logic to consider the "fuzzy" values and associations between two variables in a cognitive map (e.g., Christen, Kjeldsen, Dalgaard, & Martin-Ortega, 2015). Qualitative descriptions of causality are described in precise ways here, parameterized with a number between –1 (i.e., high negative influence) and 1 (i.e., high positive influence) at 0.1 intervals, offering 21 possible options.

5.3 | Analyzing systems based on mental models

Once relationships have been elicited and quantified, the resulting model can be developed further to run with quantitative data. In other words, the mental model provides us with a basis to quantitatively model future system states and test how a system might respond to different changes or interventions. A range of methods exists to perform these analyses, including system dynamics, agent-based models, and integrated modeling (see Voinov et al., 2018 for a review). Here, we explore one method, BBN, based on Bayes' theorem about subjective probabilities and their implications for inference. In a BBN, the links between the model variables, or nodes, are elicited using probabilities that are typically derived using expert elicitation (Martin et al., 2012), but can also be obtained through methods such as the four-step Delphi method (see McBride et al., 2012). The underlying structure of a BBN is usually a type of influence diagram, in which many variables combine to affect a selected system variable related to a stated goal. The term "belief network" expresses the relationship with mental models: these relationships are assumptions—often but not always expert assumptions (Chan, Ross, Hoverman, & Powell, 2010)—about how a system works. Thus, probabilities allow different assumptions to be used in predicting the likelihood of outcomes. The networks are used to calculate how probable an event is, and can be confirmed or adapted on the basis of empirical observations or external interventions on particular system variables that can be collected over time (e.g., Pollino et al., 2007). BBNs are particularly useful when empirical data are initially unavailable, because qualitative data (e.g., perceptions such as whether a variable is high, medium, or low) can provide a sufficient basis for a testable quantitative analysis of a system until better measure can be sought.

6 | COMPARING MENTAL MODELS

A final step in mental models research involves analyzing the models. Here, we discuss some of the more common analysis options to demonstrate that a range of choices is available to researchers and practitioners depending on the application of the mental models. To examine the diversity across models with participant-generated variables, for example, descriptive statistics can be collated on the total number of variables used in each model, variables within defined categories, and the number, strength, and nature of relationships between variables. To compare similarities and differences between mental models (e.g., between individual models or within team or shared mental models), the variables used by the participant in representing their mental model can be entered into an adjacency matrix: a spreadsheet that contains details of all relationships between all variables for each model (see Langfield-Smith & Wirth, 1992 for details). Analysis can be performed on two or more models to compare for similarities or differences (e.g., Moon & Adams, 2016).

Network analysis tools can be used on adjacency matrices of individual or team models to identify similarities between individuals in the content and structure of diagrams (e.g., Jones et al., 2014). Network analysis methods are useful for examining models, presenting an opportunity for researchers to identify dominant structural components of the system across participants to explore the complexity and heterogeneity of individual models. Measures include path length (average distance between variables), centrality and betweenness, maximum distance between variables, and the total number of connections (see Pearson & Moon, 2014).

Graph theory, which underpins diagraphs, provides matrix algebra tools that can be used to analyze the structure of complex maps and diagrams, such as whether a system is hierarchical or more democratic (see Özesmi & Özesmi, 2004). Analysis options will depend on whether the researcher or the participant generated the variables (Figure 2).

7 | LIMITATIONS OF MENTAL MODELS RESEARCH FOR CONSERVATION POLICY AND PRACTICE

A number of practical and theoretical limitations of mental models research require consideration. First, it is important that participants involved in mental models research have clear expectations of the process and outcomes, just as in any social science approach. Mental models research can be resource intensive, requiring an initial assessment of expected costs and benefits. Mental models research can also reveal new areas of conflict because the elicitation process can seek to make implicit perceptions explicit, creating a risk of identifying or prompting new or emerging conflicts and so engagement processes need to be carefully thought through and managed. Participants need to be clear about the intended outcomes of the research process, and research designers need to be aware of any aspects of the conservation context that might be beyond the reach of mental models methods.

Second, researchers need to remember that different mental models can be held about different aspects of the same system (Cannon-Bowers et al., 1993). Given a particular goal or focus, the relevant model will be "activated" (see Lindenberg, 2009). To illustrate, a person might have a mental model of a system of commoditized domesticated animal products that are acceptable to trade (e.g., cow meat, leather, milk). When asked about establishing a market for deer meat (venison) for human consumption, an individual might not call up their "commoditized domesticated animal product" model, but instead a "wild animal" model in which it is not acceptable to commoditize (and eat) deer. The importance here for research design and model application is that unless the model that is most likely to be activated in a given circumstance is elicited, outcomes anticipated from mental models research might not be realized. Follow-up interviews can be helpful, or even necessary, in understanding the structure and content of the model in more detail.

Third, and relatedly, even when a person activates a particular mental model, Wood, Bostrom, Bridges, and Linkov (2012) warn that this model will not necessarily describe that person's behavior. As Wood, Bostrom, Convertino, Kovacs, and Linkov (2012) describe it, an important distinction exists between the structure of the model (i.e., knowledge, attitudes, preferences) and the operations that are performed on that structure (i.e., reasoning and other operations performed on the mental model). The structure on its own, however, does not tell us explicitly how people will behave or necessarily how their model matches with "reality" but it can provide important context for motivations and behaviors.

8 | ADVANCING MENTAL MODELS FOR CONSERVATION

Mental models research is currently underutilized in the field of conservation biology, despite having much to offer. Understanding how people construct individual or group mental models of social-ecological systems provides opportunities to examine knowledge, assumptions, and expectations of how systems could or should respond to change. Different methods, as we have outlined, can be used in ways to reveal simple relationships within a model, or more complex dynamics. The methods can be used to elicit individuals or team models, or within a group setting to co-create a shared mental model. We encourage engagement with these methods to increase our understanding of the relationships within and between social-ecological systems for more equitable, sustainable, and effective conservation outcomes.

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