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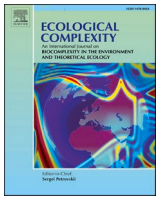

Fuzzy Cognitive Maps of Social-Ecological Complexity: Applying Mental Modeler to the Bonneville Salt Flats

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ABSTRACT

Although often limited in terms of extent or accuracy, mental models—i.e., explanations of the surrounding world and how things work within it—provide confidence and frameworks to navigate life's uncertainties. Unfortunately, differing and yet similar mental models held collectively by groups can lead to problematic behavior, misunderstandings, and conflict on large scales. Such challenges are likely familiar to natural resource managers who, in the course of their work, must consider issues that are neither simple nor exclusively ecological or social in nature. Building mental models of various groups' understanding of a complex natural resource may help managers address the impacts of resource-related behaviors but can be a difficult task when collecting modeling data from large and diverse user groups. Using a sequential, exploratory approach, our study addresses the utility of *surrogate* mental modeling to explore (a) mental models held by key players from six stakeholder groups associated with Utah's Bonneville Salt Flats (US), and (b) whether these key players were confident that their personal subjective models represented their own group's thinking about Bonneville. We sought to illuminate and compare stakeholder groups' mental models of subjectively important social and ecological concepts related to Bonneville through the use of fuzzy cognitive maps (FCMs; i.e., semi-quantitative representations of mental models) constructed in *Mental Modeler*. Analysis revealed differences among groups' FCMs and levels of perceived complexity, as well as areas of agreement regarding the strength, direction, and character of certain social-ecological relationships. Intersections and divergences in stakeholder mental models may provide logical starting points for communal knowledge-building that can perhaps lessen tension among groups attributable to conceptual misunderstandings of resource-specific complexity.

1. Introduction

Psychologist Kenneth Craik's (1943) work suggested that the human mind constructs small-scale models of reality to anticipate and understand events. As such, these mental models represent images of the world that provide perspective for navigating our lives. Because no human mind can fully or all-at-once imagine the entirety of complex entities—e.g., the world, a government, a country, etc.—we unconsciously but necessarily select only certain concepts and the relationships between them to represent the real system (Forrester, 1971). Though often simplified and limited, mental models are cognitive representations of external reality (Jones et al., 2011) that are nonetheless valuable for understanding a complex world (Johnson-Laird, 1983).

Such reductions of reality are not necessarily a liability. While often limited in extent or accuracy, mental models provide confidence and frameworks to navigate life's uncertainties. Conversely, mental models potentially come into conflict as one person's perception of reality seems incompatible with another's (Spicer, 1998), such as when espousing political leanings (e.g., Mason and Fragkias, 2018), pursuing common goals, or using common resources (e.g., Kim and Senge, 1994). This idea should be familiar to anyone who has experienced a misunderstanding based on differing perspectives.

Unfortunately, different mental models held collectively by groups can lead to misunderstanding and conflict on large scales (e.g., Crandal et al., 2020). Such challenges are likely familiar to natural resource managers who must consider many issues that are neither simple nor exclusively ecological or social in the course of their work (Miller et al., 2017). For this reason, natural resource managers must employ a similarly diverse array of approaches to complexity, resilience, and reciprocity of human and ecological variables (Berkes et al., 2008). This is

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partially due to the integration of human social processes with ecological systems in these realms of management, which necessitates acknowledging many natural resources as *social-ecological systems* (SESs; Berkes, 2017).

As integrated 'bio-geo-physical units' and their associated human social actors and institutions,[1] SESs exhibit varying degrees of complexity, uncertainty, and non-linear behaviors among system components (Glaser et al., 2008). Thus, mindfully managing natural resources as SESs entails engaging in *SES thinking*. This practice makes management processes flexible and able to engage uncertainty while building various capacities to adapt to social and ecological dynamics (Berkes et al., 2008).

More directly, however, resource management issues can be complicated by mental-model-influenced perceptions involved in—as well as affected by—resource-related decision-making (Biggs et al., 2011). Although mental models are never fully accurate or complete (Meadows, 2008), identifying and illustrating them graphically may help illuminate how people conceive of—and thus behave in—the complex world around them. This is an appealing prospect for natural resource managers because systems-thinking literature (e.g., Jones et al., 2011) suggests that mental models form the basis of shared social agreements about the nature of reality; as such, mental models can be seen as sources of behavior in social systems (Meadows, 2008). Exploring various stakeholder groups' perceptions—i.e., mental models—of the concepts, strength, and character of components within an SES may uncover implicit conflict, generate new governance solutions, and identify key cognitions that are antecedents to informal and formal adaptation behaviors (Gray et al., 2012).

To this end, this study herein explores (a) perceptions of complexity and (b) 'systems' thinking of stakeholders[2] associated with a specific SES—Utah's Bonneville Salt Flats (Bonneville, US). With the help of influential members of the Bonneville stakeholder community who were identified through a previous study's *social network analysis*, we engaged in mental modeling to produce *fuzzy cognitive maps* of stakeholders' mental models of subjectively important social and ecological relationships embodied by Bonneville. Our findings hold potential management implications for fostering collaboration among stakeholder groups for the successful conservation of Bonneville as an iconic American natural resource.

2. Background

2.1. Social network analysis

Social network analysis (SNA) is a method of revealing social interactions among individuals to understand the general characteristics of a social network. The qualities of specific relationships are revealed by enumerating actors' connections and therefore potential influence on other actors (e.g., stakeholders associated with a particular natural resource). We previously performed an SNA of Bonneville stakeholders as part of a related study (Blacketer et al., 2021; unpublished manuscript). This SNA identified influential members of each stakeholder group, i.e., *key players*[3] who were the focus of the mental modeling activities described herein. We selected key players based on specific social network metrics that are useful for identifying and engaging these influential people (as per Mbaru & Barnes, 2017). See Table 1. These individuals may be advantageously positioned to successfully implement four distinct conservation objectives. Perhaps important for addressing natural resources as SESs, these objectives include (1) rapid diffusion of conservation information, (2) diffusion between disconnected groups, (3) rapid diffusion of complex knowledge or initiatives, or (4) widespread diffusion of conservation information or complex initiatives over a longer time period (Mbaru & Barnes, 2017).

2.2. Mental models and fuzzy cognitive maps

While mental models are organized knowledge structures that individuals hold in their minds, *cognitive maps* are visual representations of those models in graphical format (Shen et al., 2017). These representations are useful tools for linking seemingly disparate concepts related to important issues (Eden et al., 1983) and for visualizing complex situations, especially applied to group thinking and problem-solving. Integrating such modeling into natural resource management—which might reveal both robust and limited understandings of complexity—may make it possible to increase managerial flexibility and responsivity to unrealized synergies between system components, particularly across key stakeholder groups (Berkes et al., 2008).

Fuzzy cognitive maps (FCMs) partially quantify relationships in cognitive maps with fuzzy values (from −1.0 to 1.0) or linguistic values to suggest the strength of causal relations, usually elicited from experts (Gray et al., 2014). FCMs are thus directed graphs that apply matrix algebra to the cognitive mapping process to semi-quantitatively explore relationships among mental model concepts. Grounded in network analysis, FCMs can be analyzed across various dimensions to detect how individuals may differently view a system (Gray et al., 2014) and have consequently been used to illuminate SES component relationships, to understand system dynamics, and to promote learning (Wei et al., 2008). Recently, increased use of FCMs has targeted their participatory approach for understanding SESs (Gray et al., 2015).

Similar to network analysis models, FCMs are semi-quantitative, graphical representations of systems that are useful for illustrating relationships (i.e., *edges)* between concepts (i.e., *nodes*) of a system, including feedback relationships (Gray et al., 2015). FCMs thus

Table 1
Conservation objectives and the SNA centrality metrics useful for attaining them, with definitions.

Conservation Diffusion Goal	Relevant Centrality* Metric	Definition of Metric
Rapid diffusion of conservation information	Closeness	The average shortest distance from a node to every other node. The more central a node is, the lower its total distance to all other nodes.
Diffusion between disconnected groups (e.g. information or initiatives)	Betweenness	The degree to which nodes stand between each other. More information passes through nodes with higher betweenness, and thus such nodes may exert more control over the network.
Widespread, long-term diffusion of information or complex initiatives	Eigenvector	The influence of a node in a network based on its connections to other high-scoring nodes.
Rapid diffusion of complex knowledge or initiatives	Degree	The number of direct connections any node has with other nodes

Note: Adapted from Mbaru & Barnes (2017); © 2017 Elsevier Ltd. All rights reserved.

* Centrality refers to indicators that identify important nodes within a sociogram, e.g. the most influential actor(s) in a social network.

[1] Per Hawe et al. (2004), actors are distinct *individuals* (e.g., residents of a neighborhood) or *collective units*—e.g., groups within an overall community).

[2] Stakeholders described herein belong to six *a priori* groups associated with Bonneville. Deeper, more theory-based stakeholder definition, identification, or selection was not part of this study.

[3] Our study defines *key players* (Borgatti, 2006) as individuals who are both (a) recipients of numerous and frequent selection and (b) themselves report numerous and frequent interactions, resulting in high centrality and degree scores in our related, but separate SNA study of Bonneville (Blacketer, et al. 2021; unpublished manuscript).

represent the relational connectivity of components—e.g., social or biophysical elements in an SES—as well as the perceived strength and direction of those relationships indicated by values assigned to the edges between nodes. See Fig. 1. Useful for mapping individual or group knowledge systems, FCMs are utilized in participatory mapping activities to help stakeholders communicate resource comprehension or co-create knowledge. FCMs have also been used in numerous disciplines to reveal system dynamics (Gray et al., 2015) and facilitate shared decision-making (e.g., Özesmi and Özesmi, 2004).

In creating a mental model, one identifies *concepts* (i.e., variables), among which both direct and indirect relationships may exist. Simply put, for each concept identified through mental modeling, an analogous, representative *component* appears in an FCM (Özesmi and Özesmi, 2004). Connections between component pairs represent direct relationships wherein one component's quantitative change drives an increase or decrease in the other component—either in the same (i.e., a positive relationship) or opposite direction (i.e., a negative relationship). The number of between-component connections in mental models can vary; however, a higher number of components indicates a higher degree of potential interactions in one's FCM (Özesmi and Özesmi 2004). Components in FCMs, therefore, serve one or both of two functions: (1) as independent variables (i.e., *drivers* or *transmitters*) that have only "forcing" functions; (2) as dependent variables (i.e., *receivers*) that have only receiving functions; or (3) as *ordinary* components that perform both driving and receiving functions (Eden et al., 1992). The *centrality* of components is a function of their overall influence in the model or the conceptual weight/importance of individual concepts (Scott, 2017). FCM *density* represents the total number of identified connections compared to possible connections among components. Thus, the higher the density, the more potential component interactions there are to consider, and the more potential implications there may be (Özesmi and Özesmi, 2004; Hage and Harary, 1983). Lastly, FCM *complexity scores* represent the ratio of receiver variables to driver variables and thus measures of the degree to which potential outcomes of driving forces are considered; higher complexity scores indicate more complex *systems thinking* represented by a model (Eden et al.1992).

FCMs offer numerous benefits for ecological modeling. These include

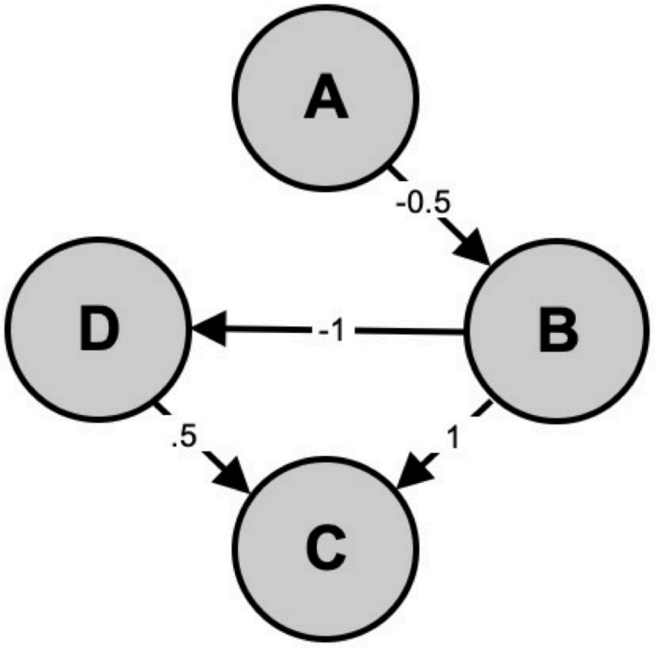

Fig. 1. Weighted edge relationships between *A, B, C,* and *D* in a basic fuzzy cognitive map; *A* is a *driving* component, *C* is a *receiving* component, and *B* and *D* are *ordinary* components (serving both driving and receiving roles). Adapted from Gray et al., 2015. Copyright © 2015 by Gray, et al.

(a) the ability to incorporate abstract as well as aggregate variables in models, (b) the ability to graphically represent relationships lacking known certainty, (c) the capacity to model complex relationships with various feedback loops, and (d) the straightforward facility for collecting and combining divergent sets of knowledge for parsing scenarios resulting from potential management actions (Özesmi and Özesmi, 2004). For these reasons, in addition to simply documenting groups' differences, this study applies fuzzy cognitive mapping to stakeholders' perceptions of social-ecological complexity inherent in the Bonneville Salt Flats.

2.3. The Bonneville Salt Flats

Bonneville is located approximately 125 miles due west of Salt Lake City in Utah's enormous West Desert. It represents the mineral remnants of the Pleistocene Epoch's Lake Bonneville, which at one time covered nearly 20,000 square m iles—roughly the size of modern-day Lake Michigan—with a maximum depth of 1000 feet (Hunt et al., al.,1953). Topographically isolated due to techtonic activity approximately 14,000 years ago (Baxter, 2018), Bonneville became a terminal basin from which water escaped only through evaporation. The mineral content of that immense volume of long-since-evaporated water is now accumulated on the playa floor and in subsurface brine aquifers.

The vast, white salt pan commonly associated with Bonneville, however, represents but one phase in seasonally-changing character that cycles annually through flooding, evaporation, and desiccation (Bowen et al., 2017; Lines, 1979). Importantly, it is specifically Bonneville's dry, well-formed salt pan that permits safe pedestrian and vehicular access to the playa. Even the slightest bit of summer precipitation can soften the crust—leaving it anywhere from tacky to sludgy to nearly dissolved—making foot or wheeled transit at least impractical, if not impossible. Thus, the seasonal expanse of a solid salt crust enables nearly all of Bonneville's recreational use .

Since the 1960s, however, the volume, thickness, and overall area of Bonneville's salt crust have objectively decreased (Kipnis and Bowen, 2018). The decline of the salt crust has consequently fueled tension among stakeholder groups, namely between the land speed racing community—which requires numerous miles of thick, hard salt crust to safely accelerate to and decelerate from hundreds of miles per hour (Bowen et al., 2017)—and the U.S. Bureau of Land Management, which manages permits and leases for all activities at Bonneville. Since 1997, efforts to dissolve and return stockpiled waste salt from industrial extraction—often referred to as the *Salt Laydown* or *Brine Return*—have endeavored to replenish the salt crust (Kipnis and Bowen, 2018). In addition to these stakeholders, other groups recognized herein are academic researchers, media professionals, artists, local community members, and mining employees—all of whom have an interest in Bonneville's future sustainable use. Bonneville thus represents an excellent living laboratory for stakeholder mental modeling of social and ecological concepts and for investigating perceptions of complexity related to a specific resource.

2.3.1. Research purpose, questions (RQs), and academic contributions

All people hold mental models that help them make sense of, navigate, and function in various environments and the world at large. Without understanding the influence of mental models on natural resources, however, the resultant impacts from those behaviors cannot be easily anticipated or proactively addressed. It is first necessary, though, to construct and analyze such models to identify any structure, commonalities, or disparities that may vary based on the character of individuals' or groups' relationships with a particular resource. Thus, our study's purpose was to illuminate influential stakeholders' mental models of important concepts related to Bonneville's social-ecological complexity. We pursued this understanding by constructing FCMs to represent these individuals' mental models, the analysis of which reveals implications for better managing natural resources as the complex

social-ecological systems that they are.

Our study addresses four primary research questions regarding stakeholder perceptions of SES complexity. Our first question (RQ1) asked, *"What important concepts do stakeholders' mental models hold when thinking about Bonneville as an SES?"* That question was addressed through interviews with *key player* representatives from each stakeholder group. We built FCMs with interview data in the *Mental Modeler* software application to graphically represent these individuals' mental models of Bonneville. Model analysis addressed RQ2 and RQ3: *"How does the structure of stakeholders' mental models—and therefore FCMs—of Bonneville differ?"* and *"To what extent do stakeholder groups similarly perceive correlations between important Bonneville concepts?"* Lastly, to address whether Bonneville stakeholder groups espouse similar mental models, RQ4 asked, *"How confident are key players that their FCMs represent Bonneville concept relationships perceived by the average member of their stakeholder community?"* Taken together, these four questions sought to address how stakeholders perceive the complexity and influence attributed to what they profess to be important concepts related to the social-ecological system that binds them together.

Our study endeavors to primary fill two gaps in scholarship. Although many studies have applied mental modeling to social-ecological systems (e.g., Gray et al., 2015) and informed natural resource management (e.g., Van Den Broek, 2018), none have applied mental modeling to a salt flat landscape like Bonneville, which is unique in its stark aesthetics as well as in its human users. Second, no known natural resource management studies have applied *surrogate* mental modeling, wherein knowledgeable key players in a social network help create FCMs that may represent their stakeholder groups' social-ecological perceptions of a mutually valued resource. This study thus endeavored to reveal the utility of surrogate mental modeling of the Bonneville Salt Flats to help compare stakeholders' mental models of natural resource-related social-ecological complexity. Taken together, these contributions can help reveal how stakeholders perceive the Bonneville Salt Flats and perhaps other playa landscapes as social-ecological systems.

3. Methods

We applied a sequential, exploratory approach (Creswell & Plano-Clark, 2017) in three phases to reveal Bonneville stakeholders' mental models through fuzzy cognitive mapping. This entailed interviewing representatives from key stakeholder communities and using the interview data to build FCMs to identify, display, and compare mental models (Axelrod, 1976). Created in *Mental Modeler* (Gray et al., 2013), these FCMs provided parameterized concept models that were translated into semi-quantitative maps for examining pair-wise structural relationships between model components.

3.1. Initial sampling

Phase I consisted of semi-structured interviews ($n = 22$; M_{minutes}=35) via telephone with members of six *a priori* Bonneville stakeholder groups: (1) the academic research community; (2) the land speed racing community; (3) federal land managers; (4) citizens of the city of Wendover and greater Tooele County, Utah; (5) news/journalism professionals, and (6) a mineral extraction industry near Bonneville. We adapted Seidman's (2013) three-interview process following recommendations by Verbos et al. (2018) and Zajchowski et al. (2019) and collected data about perceptions, insights, and experiences in a single interview. These initial interviews endeavored to gain an understanding of Bonneville-related social and biophysical concepts that stakeholders perceived to be important (as per Gray et al., 2013).

Following a brief discussion of study goals, we asked participants to list the top ten social or biophysical concepts that they believed were influential in shaping Bonneville. We recorded and compiled a list of 45 total concepts that we later shared with influential Bonneville stakeholders (i.e., key players) selected for the final data collection phase.

3.2. Identifying and engaging key players

We used three *centrality* scores—closeness, betweenness, and eigenvector—in addition to both weighted and total *degree* scores from our separate SNA (Blacketer, et al., 2021; unpublished manuscript) to identify some of Bonneville's key players. Table 1 contains definitions and justification for using these measures, as per Mbaru and Barnes (2017). Next, we selected the two actors from each of the six *a priori* stakeholder groups who had the highest degree and centrality scores. As key players, these individuals appeared in network sociograms as points (i.e., *nodes*) with numerous rays (i.e., *edges*) connecting them to other nodes (Scott, 2017). Due to their positions in the social network, key players hold networks together, and their removal can result in fragmented cliques and isolated individuals.

Serving as hubs through whom numerous Bonneville-related social interactions occurred during the data collection year, key players represent a sample that was potentially well-qualified to speak on behalf of their stakeholder communities, specifically about perceptions of Bonneville's social-ecological complexity. Because they were objectively identified by the SNA study, these key players' mental models were solicited in Phase II as representative of their own stakeholder groups' thinking about Bonneville. Key players' FCMs—although created individually—thus serve as surrogate models for each stakeholder community.

During each interview ($n = 11$, $M_{minutes}$=45), we asked key players, *"What are the 5–15 concepts you believe are 'important to consider' when thinking about Bonneville as a social-ecological system?"* See Table 2. Although we also briefly discussed the definition of social-ecological systems, if interviewees did not fully understand the 'social-ecological system' part of the question, we rephrased it as, *"... when thinking about Bonneville's use, management, or ecology."*

These conversations were highly qualitative and narrative in nature but yielded semi-quantitative mental model data for FCM analysis. During each interview, we built a correlation matrix with participants' reported concepts, the list of which was entered in both the leftmost column and across the topmost row of the matrix. See the example in Fig. 2. Moving across and down the matrix, we asked participants to communicate five things for each correlation pair: (1) if they perceived a direct relationship to exist, (2) if so, which concept was a driving variable and which was a receiving variable, (3) whether an increase or decrease in the driver would produce likewise or opposite increase or decrease in the receiver, (4) whether the relationship was low, medium, or high in strength; and lastly (5) how confident they were that other members of their community group would agree with that

Table 2
'Important to consider' Bonneville concepts identified in Phase II qualitative interviews

Salt Crust Thickness	Ground Water	Media Attention
Wind	Percolation	Precipitation/Flooding
Annual Precipitation	Summer Temperature	Subsurface Brine Movement
Salt Crust Area	I-80 / Public Access	Stockpiled Waste Salt
Salt Crust Composition	Salt Brine Return	Drainage/Canal Structures
Erosion	Mineral Extraction	Evaporation
Water Table Level	Salt Brine Removal	Drying/Desiccation/ Crystallization
Mgmt. Activity Level	Mining Leases	Track Prep/Grooming
Dike/Berm Structures	Driving on Salt	Quality of Management
Surface Brine Movement	Stakeholder Blame/ Tension	Microbe Action/Population
Soil/Sediment	Misinformation	Chemical/Fuel/Oil Pollution
	General Racing Activities	

Note. Concepts were neither presented in any particular order, nor was any ranking or relation among concepts implied.

	Salt Crust Thickness	Mineral Extraction	Precipitation/ Flooding	Salt Crust Area
Salt Crust Thickness				0.75
Mineral Extraction	-0.75			-0.75
Precipitation/ Flooding	0.5	-0.75		0.5
Salt Crust Area	0.75			

Fig. 2. An example of an FCM matrix produced by Mental Modeler showing positive and negative correlations; driving components are at left and receiving components are across the top.

characterization (on a Likert-type scale of 1= 'not at all confident' to 7='very confident,' as per Mental Modeler's built-in parameters). Participants were given adequate time to cogitate and/or provide any explanation they felt necessary for each correlation. Their list of concepts and perceived correlations between individual concepts provided all FCM data, thus answering RQ1.

3.3. FCM construction and analysis

Using the free, online Mental Modeler interface at www.mentalmodeler.org (Gray et al., 2013), we created one FCM for each key player in Phase III. This entailed drawing pairwise relationships between reportedly related concepts using weighted, directional arrows (i.e., *edge relationships*) to indicate positive or negative relationships with high (0.75), medium (0.5), or low (0.25) strength.

Mental Modeler calculated network structural characteristics for each FCM. At the model level, these measures included the number of (a) component connections, (b) driving variables, (c) receiving variables, and (d) ordinary variables, as well as (e) density, (f) diameter, and (g) complexity measures of each model. See Table 3. Mental Modeler also provided component-level metrics, including (a) centrality, (b) in-degree, (c) out-degree, and (d) type for each component. Data analysis following stakeholder interviews addressed RQs 2, 3, and 4.

4. Results

Of the 12 potential participants identified as key players, 11 individuals participated in the mental model exercises used to construct FCMs. Following those interviews, FCM construction and analysis yielded the following results.

4.1. Important SES concepts in stakeholders' mental models (RQ1)

Participants collectively selected 32 of the 45 original concepts in Table 2. The frequency with which any of these concepts was reported as 'important' by one or both key players in a stakeholder group ranged from one to eight times. This list provided the basis for answering RQ1: "*What important concepts do stakeholders' mental models consider when thinking about Bonneville as an SES?* The top ten concepts reported as 'important to consider' by four to eight participants from two or more stakeholder groups were *Salt Crust Thickness* ($n = 8$), *Evaporation* ($n = 7$), *Salt Brine Return* ($n = 6$), *Precipitation/Flooding* ($n = 5$), *Subjective Quality of Management* ($n = 5$), *General Racing Activities* ($n = 5$), *Salt Brine Removal* ($n = 4$), *Mineral Extraction* ($n = 4$), *Salt Brine Return* ($n = 4$), and *Track Preparation/Grooming* ($n = 4$).

4.2. Structure of FCMs (RQ2)

Mental model-based FCM structure varied somewhat widely (see Table 3). The total number of FCMs components ranged from 6 to 13, and the number of connections per component correspondingly ranged between 1.2 and 6.4. Across all FCMs, the number of components functioning exclusively as drivers or receivers ranged from 1 to 3, and ordinary components—i.e., functioning as both driver *and* receiver depending on the relationship—ranged from 2 to 13. Regarding FCM complexity, the total number of connections ranged from as few as 8 to as many as 90 connections, with FCM network densities ranging from 0.25 to 0.49. Resultant complexity scores—for which higher scores indicate more complex systems-thinking based on the extent to which outcomes of driving forces are considered (as per Eden et al., al.,1992)—ranged from 0 to 1.5.

The centrality of the ten most frequently reported mental model concepts—and thus FCM components—appears in Table 4. These are useful for understanding how these concepts hold mental models together; they also provide a basis for answering RQ3: "*To what extent do stakeholder groups similarly perceive correlations between important Bonneville concepts?"* The lowest individual component centrality was 1.25 for *Quality of Management*, reported by the Media community. The highest individual component centrality—9.9 for *Salt Crust Thickness*—was reported by the Land Speed community. The mean centrality for each component ranged from 3.3 to 6.5.

Figs. 3 and 4 display examples of FCMs representing relative extremes in terms of (a) the number of SES components that key player participants deemed 'important to consider' regarding Bonneville as an SES, and (b) the extent of components' interconnections in each model. Fig. 3 presents a relatively simple model comprised of the six components that a Media actor deemed to be 'important to consider.' Conversely, the Land Speed FCM in Fig. 4 includes 13 components and 58 pairwise relationships. In both of these figures, blue arrows represent positive correlations, whereas orange arrows represent negative correlations. Thicker lines represent stronger relationships.

4.3. Perceptions of important concepts and relationships (RQ3)

Numerous pairwise relationships appeared between stakeholders' top ten reported concepts—i.e., FCM components—with varying agreement regarding component correlations. The matrix in Table 4 addresses the extent to which stakeholder groups similarly perceive correlations between 'important' Bonneville concepts. Many correlations were reported by only one or two groups, but several noteworthy correlations were perceived to exist by three or more groups.

The component correlation with the greatest agreement among groups was that between *Salt Brine Return* (driver) and *Salt Crust Thickness* (receiver). Academia, Land Speed, Media, and Wendover reported a high positive correlation between these components, with a fifth group—Land Management—reporting a certain but unspecified relationship.

Three groups—Academia, Land Speed, and Media—reported a positive correlation between *Salt Brine Return* and *Salt Crust Area*, but whereas Academia rated this correlation strength 'medium,' the others rated it 'high.' Similarly, these three groups reported a relationship between *Salt Crust Thickness* and *Salt Crust Area*, and while Academia was uncertain of the character of the correlation, Land Speed and Media reported it as a positive correlation; too, they differently perceived the strength as 'high' and 'medium,' respectively.

Three groups reported a high-strength correlation between *Precipitation/Flooding* and *Evaporation*, although the Academic actors were split on the direction; Industry and Wendover reported this correlation as negative. Three groups reported a relationship between *Precipitation/Flooding* and *Mineral Extraction.* Land Speed and Media disagreed about the direction while reporting a high-strength correlation, and Media reported a medium-strength, positive correlation.

Table 3
FCM network structure by stakeholder group and participant.

Stakeholder Group	Actor*	Total Components	Connections per Component	Component Type #Drivers	#Receivers	#Ordinary	Total FCM Connections	FCM Density	FCM** Complexity Score
Academia	138	8	2.63	2	1	5	21	.38	.5
	222	14	6.43	2	1	11	90	.49	.5
Land Speed	450	13	4.46	2	0	11	58	.37	0
	324	14	5.79	1	1	13	81	.45	1
Land	396	8	3.25	2	1	5	26	.46	.5
Management	330	8	3.5	1	1	6	28	.5	1
Wendover/	342	8	1.75	2	3	3	14	.25	1.5
Tooele	297	7	2.43	2	1	4	17	.40	.5
Media	207	6	2	0	0	6	12	.40	0
	156	8	2.75	3	2	3	22	.39	.67
Mining/Industry	213	6	1.33	2	3	2	8	.267	1
	159	NR	NR	NR	NR	NR	NR	NR	NR

Note: *Indicates the anonymous ID number for key players identified in the separate social network analysis study (Blacketer et al., 2021; unpublished manuscript); **Scores generated by *Mental Modeler*. NR="No Response" provided by this actor.

Table 4
Matrix of top ten FCM components' centralities by stakeholder group.

FCM Component	Component Centrality by Stakeholder Community Academia	Land Speed	Land Mgmt.	Mining / Industry	Media	Wendover / Tooele	Mean
Evaporation	5.12*	–	5.12	2.75	–	3.75	4.19
General Racing Activities	4.25*	9.0	4.51*	–	–	–	5.92
Mineral Extraction	–	8.0	4.0	0.5	2.25	–	3.69
Precipitation / Flooding	3.93*	4.75	–	2.75	2.76	2.7	3.38
Subjective Quality of Mgmt	2.5	6.88*	–	–	1.25	3.25	3.47
Salt Brine Removal	2.8*	6.5*	–	–	–	–	4.65
Salt Brine Return	3.25	6.5*	2.5	–	1.5	2.95	3.34
Salt Crust Area	7.0	9.75*	–	–	2.75	–	6.50
Salt Crust Thickness	5.75	9.88*	3.25	–	2.13	3.64	4.93
Track Preparation / Grooming	–	–	4.24	2.0	–	3.75	3.33

Note: *Denotes mean for both key players in group, as opposed to only one actor in group. Cells without numeric values indicate unselected components.

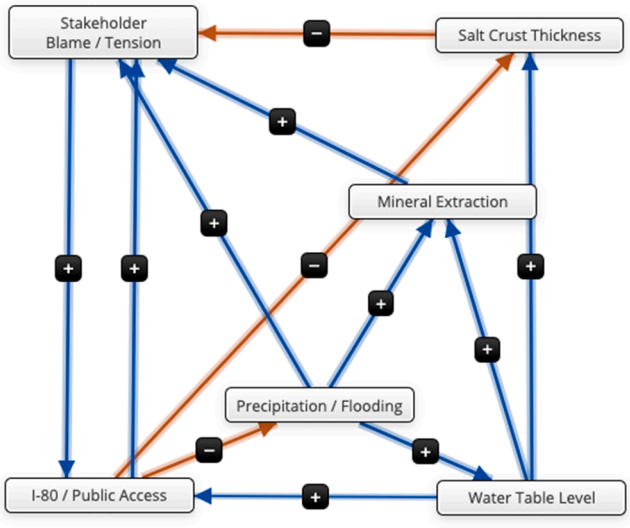

Fig. 3. A media community member's FCM of six 'important to consider' components of Bonneville's social-ecological complexity.

Academia, Land Management, and Wendover reported a high-strength positive correlation between *Evaporation* and *Salt Crust Thickness*. Industry, Land Management, and Wendover reported a high-strength positive correlation between *Evaporation* and *Track Preparation*.

Land Speed and Wendover reported a high-strength positive correlation between their perceptions of *Subjective Quality of Management* and *Salt Crust Thickness*. Although Media agreed that this relationship existed, the actor reporting that perception was unsure of the correlation's character. Similarly, Land Management and Land Speed agreed that a positive correlation exists between *Salt Brine Return* and *General Racing Activities*, but disagreed on the strength, while Academia acknowledged an unclear relationship between those two components.

For several concept relationships, key players strongly believed a relationship to exist, but could not conceptualize or communicate how the relationship worked. These were recorded as unspecified relationships between driving and receiving components and are denoted in Table 5 with a question mark (?).

4.4. Stakeholder confidence in the representativeness of FCMs (RQ4)

Key players' confidence refers to their level of certainty regarding whether their characterization of components' pairwise relationships is shared by their stakeholder community. Including only the values for identified relationships between components—i.e., $m_{confidence}$ = (sum of confidence scores for reported relationships) / (number of relationships for which confidence was reported)—these confidence scores ranged from 4.5 ('slightly confident) to 6.6 (nearly 'fully confident') for each overall FCM. The overall mean of 5.7 across all FCMs equates to 'moderately to very high' confidence on the Likert scale. See Table 6. This relatively high level of confidence suggests that key players believed their own perceptions of component relationships to be representative of those held by typical members of their respective groups, as per RQ4. While confidence was assessed for each pairwise component relationship, on very few occasions did key players report low levels of confidence for their characterizations. In such cases, the actors suggested that despite the importance of the two concepts separately, their low reported confidence for a specific correlation between those concepts was attributed to their own uncertainty. These occurrences of low confidence are responsible for some of the unspecified correlations denoted with a question mark (?) in Table 5.

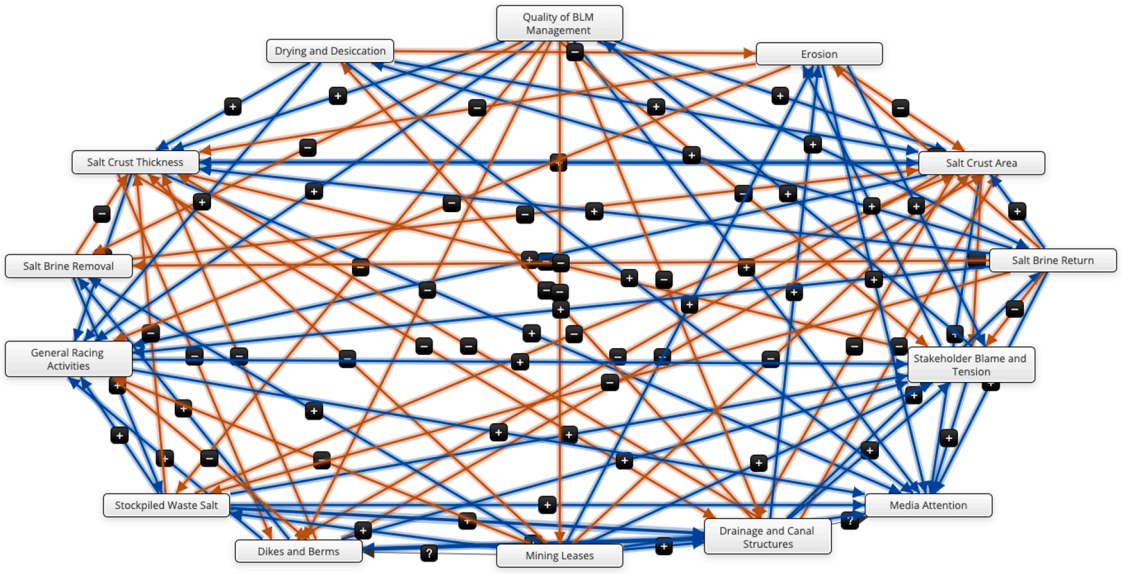

Fig. 4. A land speed community member's FCM of 13 'important to consider' components of Bonneville's social-ecological complexity.

Table 5
Matrix showing key players' reported correlations between the top ten reported driving and receiving components.

Driving Components ↓ / Receiving Components →	Evaporation	Mineral Extraction	Precip. / Flooding	Subj. Quality of Mgmt.	(General) Racing Activities	Salt Brine Removal	Salt Brine Return	Salt Crust Area	Salt Crust Thickness	Track Prep. / Grooming
Evaporation	—				AC: H+/- LM: 2H+	AC: H+	WT: H+	AC: H+	AC: H+ LM: H+ WT: 2H+	IM: H+ LM: 2H+ WT: H+
Mineral Extraction		—			LM: L-	LS: H+	LS: ?	LS: H-	LM: H-	LM: L-
Precip. / Flooding	AC: H+/- IM: H- WT: H-	LS: H- ME: H+ IM: M+	—		AC: 2H-	AC: ? LS: H+	LS: H+	AC: H- LS: M+	AC: M+ WT: H-	IM: H-
Subj. Quality of Mgmt.		LS: H-		—	AC: M- LS: H+	AC: ? LS: H-	LS: 2H+ ME: ?	LS: 2H+ ME: ?	LS: H+ ME: ? WT: H+	
Gen. Racing Activities					—			AC: L-	AC: L- LM: M-	
Salt Brine Removal					AC: M-	—	AC: ?	AC: H- LS: 2H	AC: H-	
Salt Brine Return	LM: H+	LS: M-			AC: ? LS: H+ LM: L+	AC: ? LS: 2M-	—	AC: M+ LS: 2H+ ME: H+	AC: H+ LS: H+ LM: ? ME: H+ WT: H+	LM: L+ WT: H+
Salt Crust Area	AC: H+				LS: H+			—	AC: ? LS H+	
Salt Crust Thickness					LS: H+			AC: ? LS: 2H+ ME: M+	—	WT: H+
Track Prep. / Grooming					LM: 2H+				LM: M-	—

Notes: Group abbreviations as follows: AC = Academia; LS = Land Speed; LM = Land Management; WT = Wendover/Tooele; ME = Media; IM = Industry/Mining. Notation in parentheses indicates strength (L=Low, M=Medium, H=High), and direction of perceived correlation (positive or negative). If both members of a group reported identical correlations, notation is preceded by a '2.' Question marks (?) denote identified but unspecified correlations.

5. Discussion

Our study contributes to several realms of scholarship related to social-ecological systems, mental modeling, fuzzy cognitive mapping, and natural resource management research. Conceptually, by focusing on subjectively 'important to consider' concepts in mental models of SESs—for which perceptions are implicit—the study links to varied research about human perceptions related to natural resources.

More specifically, our study engaged in mental modeling using the possibly untried method of representative or *surrogate* mental modeling of a complex SES. This process engaged knowledgeable Bonneville community members—who were objectively selected through social network analysis in a separate study—to representatively characterize relationships between pairs of 'important to consider' social and/or ecological concepts related to Bonneville. Our study thus explored surrogate mental modeling's utility for comparing perceptions of natural resource-related social-ecological complexity.

The first consideration in regard to interpreting mental model consistencies and discrepancies entails whether any particular stakeholder might be additionally identified as an *expert* regarding Bonneville. The

Table 6
Participants' confidence that their FCMs represent their group's mindset.

Stakeholder Group	Actor*	Mean Confidence**
Academia	138	5.8
	222	4.5
Land Speed Racing	450	6.5
	324	6.1
Land Management	396	6.6
	330	5.1
Wendover / Tooele County	342	5.0
	297	5.9
Media	207	5.6
	156	5.1
Mining / Industry	213	6.4

Note: *Anonymous actor ID numbers for key players identified in the separate SNA (Blacketer et al., 2021; unpublished manuscript). Mean confidence was calculated by dividing the sum of reported pairwise confidence values by the number of reported confidence values.** Confidence was rated on a on a Likert-type scale (1= 'not at all confident' to 7='very confident').

term "expert" suggests a person upon whom society and/or their peers attribute possession of special knowledge about the matters being elicited (Garthwaite et al., 2005). While anyone could be considered an expert regarding their own individual position or experience with Bonneville, it is clear that several key players possessed extensive knowledge of Bonneville's complexity. Academic community members, particularly, demonstrated great facility with relationships among Bonneville-related social and ecological concepts. This is attributable to years of accumulated, validated, and synthesized research performed by generations of scientists. The acquisition of such knowledge is admittedly important for assessing the objective accuracy of resource-specific relationships.

The two other groups that expressed facility with their reportedly important concepts were members of the Land Speed and Land Management communities. The two representatives from Land Speed identified 13 and 14 'important to consider' concepts regarding Bonneville's complexity, and both of these individuals spent considerable time explaining the resultant 58 and 81 total relationships between concept pairs. Bonneville Land Managers each reported only eight concepts as 'important to consider,' representing 24–26 relationships.

Fewer identified concepts, however, do not necessarily suggest less complex thinking about Bonneville. Logically, Land Speed participants' identification of more numerous social and ecological concept relationships could be attributed to (a) long personal histories of using Bonneville and (b) their overall activity-specific goals (e.g., safely breaking land speed records) that require intimate knowledge of salt crust character and formation. Land Speed community members may therefore be quick to share their insight regarding the many elements that affect how racers can meaningfully engage with Bonneville. Land Managers, however, have different goals regarding Bonneville. They require a significant understanding of social and ecological complexity to effectively perform their work and must additionally consider numerous management objectives; for their purposes—i.e., high-level oversight of a large natural resource for both recreation and mining—eight concepts were perhaps adequate for modeling how they engage with Bonneville.

More broadly, 'complexity thinking' about Bonneville entails focusing on the subjectivity of our research question, which asks specifically for concepts that key players believed to be 'important to consider.' Thus, the concepts any person identified as important could be influenced by many factors, such as past use history or resource-related goals. Despite the potential for these concepts to be wildly divergent, they were ultimately rather concise both in their initial identification as well as in their selection during mental modeling interviews. A total of 32 concepts were chosen as 'important to consider' when thinking about Bonneville as a social-ecological system, and ten of those concepts were reported by four or more of the 11 interview participants. See Tables 4 and 5.

The implication of these points relates to how complexity-thinking and SES science can be translated for stakeholders' use. For the Land Speed community, this might mean measuring, quantifying, and interpreting the relationships among salt crust features and phenomena that racers have historically observed, but perhaps not assessed quantitatively. For Land Managers, it may mean helping predict cascades of influence attributable to change or disruption of social or ecological phenomena so that managers can effectively write policy for emergent situations. This is the goal of *translational ecology*—a field of science in which individuals with diverse disciplinary expertise and skillsets engage across social, professional, and disciplinary boundaries to assist decision-makers in bringing practical environmental solutions to fruition (Schwartz et al., 2017).

Perhaps the key takeaway from our study is the potential utility of *surrogate mental modeling*, wherein influential stakeholders provide key information regarding the perceptions of their resource-related stakeholder groups. While not equal to larger-scale knowledge-building through collaborative mental modeling, this study advances the possibility that mental modeling by community leaders or representatives—which could be the only option when entire stakeholders groups are not accessible—can nonetheless provide valuable information about the mindsets of resource users. Using representatives to model collective mindsets, however, should additionally consider the difference between true *surrogates* selected by researchers versus *proxies* selected by stakeholder groups themselves.

5.1. Study considerations and future research

Despite its contributions, our study contained other considerations that influenced its outcomes. Regarding RQ1—wherein participants proffered 'important' concepts—some people struggled to characterize certain relationships due to the specificity, ambiguity, or subjectivity of the concepts provided for selection in the mental modeling exercise. Though that list was compiled through many previous interviews, participants later regarded some of the concepts as too specific, not specific enough, or as a body of concepts too divergent in their relevance, scale (e.g., socially, ecologically, geologically, economically), or subjective definitions. Future similar research might seek better bounding or expert opinion to generate a concept list for comparing across groups to reduce concerns about scale, subjectivity, and relevance. Conversely, perhaps soliciting numerous mental models at different scales—and then linking them—might be a laudable approach to truly mapping perceived SES complexity.

Furthermore, we recognize that a crucial test of the utility of our approach would have entailed comparing each key player's FCM with a collective FCM representing average members of each stakeholder group (i.e., non-key players' FCMs). Such a comparison may validate whether we could more confidently suggest that key players could speak accurately for their groups. Due to data collection difficulties in our related SNA research that informed the study herein, we did not perform such a comparison due to anticipating low (and therefore problematic) response rates to additional mental model/FCM interviews. Testing our approach thus remains an endeavor of future research.

Related to general systems complexity, another potential limitation regards the application of our SES research angle. We partially endeavored to reveal differences in potential FCM complexity among stakeholder groups; we did not, however, purport that more complex FCMs are preferable. As mentioned in the Introduction, mental models are typically bounded by experience and understanding, and although sometimes inaccurate or incomplete, they remain useful for navigating life. Regarding larger SESs, one way to deliberately bound a system for research purposes (e.g., modeling) is to consider the *Rule of Hand* (Allen and Garmestani, 2015) . This approach suggests that five variables at different scales can adequately capture a broad range of system complexity. Walker et al. (2006) further explain that more complex

models can be unnecessary for explaining primary cause-and-effect patterns, adding that additional model complexity may even mask primary relationship patterns due to (a) our human ability to understand only low-dimensional systems and (b) because only a few variables ever appear dominant in observed system dynamics.

Thus, Bonneville stakeholders may not need complex mental models to cooperatively use or manage use Bonneville for their chosen purposes. Nonetheless, agreement about tangible, objectively measurable, or evidentiary correlations among social and biophysical concepts is certainly desirable. Future research that aims to identify important SES concepts should perhaps ask participants to rank their selections by importance. Perhaps by identifying each stakeholder's (or group's) top five most important concepts (as per the Rule of Hand), conversations about resources can begin with fundamental concepts before accordingly expounding upon additional layers of complexity.

RQ2 addressed FCM network structure across Bonneville stakeholder groups. Despite similarities regarding the most-included concepts, several FCMs were structurally different even within-group. Aggregating these models was not deemed to be appropriate because of the low number of overlapping concepts between same-group participants. This is simply a shortcoming of the study's small sample size, which was a product of focusing on key players instead of modeling perceptions of all—or at least numerous—stakeholder group members. When possible, representatively aggregating numerous individual-level models into group models would be preferable for depicting accurate group perceptions—something we originally desired to do before encountering low response rates in our SNA data collection efforts. Ideally, mental modeling of natural resource-related stakeholder groups would entail collaborative co-construction of mental models—an in-person process during which many individuals could discuss and debate their thinking regarding social-ecological complexity attributed to a resource.

Complexity scores were also problematic. Because they represent the ratio of receiver variables to driver variables, two FCMs—one from Land Speed Actor and one from Media—contained no exclusively *receiving* components; these models thus had complexity scores of zero. Characterizing models with numerous components and correlations as having zero complexity seems unrepresentative of those actors' mental models, which are demonstrably laden with complex considerations. Thus, a different scoring method may be in order; Wiesner's and Ladyman's (2019) recommendations for assessing complexity may be useful in this regard.

Regarding RQ3—agreement among groups' reportedly important SES concepts—the same previously discussed concerns arose. Without full confidence in the concept list, the pairwise relationships between concepts are called into question. Nonetheless, concept relationships that are consistent from group to group are potentially valuable places to begin discussion and knowledge-building among stakeholders. Due to various social circumstances, stakeholder groups may engage one another with suspicion and distrust, and so pointing out concepts and related relationships with which they agree may be a wise place to begin collaborative activities. In this study, members of four out of six stakeholder groups confidently and consistently characterized the relationship between *Salt Brine Return* (as a driver) and *Salt Crust Thickness* (as a receiver). Similarly, three groups consistently characterized the correlation between *Salt Brine Return* and *Salt Crust Area.* These areas of agreement are likely good places to begin additional conversation around Bonneville's use and management.

Lastly, key players' confidence—that their FCMs represent the perspectives of their communities (RQ4)—was reported as a mean for each model. Reporting confidence for every concept relationship proved awkward with so much diversity in 'important' concepts and the relationships between them; it was thus determined to be a less-than-helpful way to present the data. Furthermore, the validity and overall accuracy of confidence at the group level is called into question due to the low sample size; again, this would be overcome by engaging in collaborative mental modeling with numerous individuals.

Discussed previously, however, any person may be considered an expert on their own experience or viewpoint; this is effectively what we asked of participants—to report their understanding of important Bonneville-related concepts (and the relationships between those concepts) and to rate their confidence that the same perspective is shared by their peers. Their high confidence in the representativeness of their mental models perhaps suggests that some participants may see themselves as experts. Thus, characterization as an expert—objectively or subjectively—may relate to participants' assertions of confidence in the accuracy of their mental models. Future research regarding perceptions of important resource-related SES concepts might explicitly assess participants' objective or subjective level of resource-related knowledge on a scale of 'zero knowledge' to 'expert-level knowledge' as a single metric.

6. Conclusion

The partial illumination of stakeholder perceptions of important social-ecological concepts and relationships is likely a good place to begin larger discussions about the overall complexity of the unique natural resource that Bonneville represents. Insomuch as groups agree or disagree on important concepts, the act of identifying intersections among concepts in mental models held by groups and/or individuals is a logical starting point for communal knowledge-building (Langfield-Smith, 1992). In the hands of this study's influential key players, the findings herein—and their resultant implications—might be usefully disseminated into the larger Bonneville community to lessen tension among stakeholder groups that are perhaps rooted in conceptual misunderstandings of social-ecological complexity.

Although Bonneville is arguably both socially and ecologically complex, many people who are intimately connected to this resource may not see it that way, owing to its stark aesthetics and reputation for barrenness. Our study thus sought to reveal how certain stakeholder groups—who perhaps understand and use Bonneville the most—conceive of its complexity. Therefore, this study suggests that illuminating landscape-specific mental models can contribute to better understanding and managing natural resources as the complex social-ecological systems that they truly are.

CRediT authorship contribution statement

Michael P. Blacketer: Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Conceptualization, Methodology. **Matthew T.J. Brownlee:** Supervision, Funding acquisition, Writing – review & editing, Conceptualization, Methodology. **Elizabeth D. Baldwin:** Writing – review & editing. **Brenda B. Bowen:** Supervision, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors have no conflict of interest.

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