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Linking knowledge and action through mental models of sustainable agriculture

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Linking knowledge to action requires understanding how decision-makers conceptualize sustainability. This paper empirically analyzes farmer "mental models" of sustainability from three winegrape-growing regions of California where local extension programs have focused on sustainable agriculture. The mental models are represented as networks where sustainability concepts are nodes, and links are established when a farmer mentions two concepts in their stated definition of sustainability. The results suggest that winegrape grower mental models of sustainability are hierarchically structured, relatively similar across regions, and strongly linked to participation in extension programs and adoption of sustainable farm practices. We discuss the implications of our findings for the debate over the meaning of sustainability, and the role of local extension programs in managing knowledge systems.

network analysis | collaborative policy | cooperation | agricultural decision making

One of the core goals of sustainability science is understanding how practitioners make decisions about managing social-ecological systems (1). In the context of sustainable agriculture, an important research objective is quantifying the economic, environmental, and social outcomes of different farm management practices (2). However, it is equally important to understand how farmers conceptualize the idea of sustainability and translate it into farm management decisions. The innumerable and often vague definitions of sustainable agriculture (3, 4) make this a challenging task, and fuel the debate about linking sustainability knowledge to action. This debate will remain largely academic without empirical analysis of how farmers think about sustainability in real-world management contexts. These questions are not only relevant to agriculture, but also to all social-ecological systems and the knowledge networks that are in place to support decision making.

This paper addresses these issues by analyzing farmer "mental models" of sustainable agriculture. Mental models are empirical representations of an individual's or group's internally held understanding of their external world (5, 6). Mental models reflect the cognitive process by which farmer views about sustainable agriculture are translated into farm management decisions and practice adoption. Our mental models were constructed from content coding of farmers' written definitions of sustainable agriculture, and were analyzed using network methods to understand the relational nature of different concepts making up a mental model.

We test three hypotheses about mental models of sustainable agriculture. First, mental models are hierarchically structured networks, with abstract goals of sustainability more central in the mental model, which are linked to peripheral concrete strategies from which practitioners select to attain the goals. Second, goals are more likely to be universal across geographies, whereas strategies tend to be adapted to the specific context of different social-ecological systems. Third, practitioners who subscribe to central concepts in the mental model will more frequently exhibit sustainability-related behaviors, including participation in extension activities and adoption of sustainable practices.

Our mental model data were drawn from farmers in three major American viticultural areas in California: Central Coast, Lodi, and Napa Valley. California viticulture is well suited for studying sustainability. Local extension programs have used the concept of sustainability since the 1990s (7, 8), and farmer participation in sustainability programs is strong (9–13). Furthermore, viticulture is geographically entrenched (14), with viticultural areas established on the basis of their distinct biophysical and social characteristics (15, 16). Hence, we expect winegrape growers to have well-developed mental models of sustainability, with geographic variation reflecting social-ecological context.

Theoretical Background

Mental Models. Mental models are empirical representations of an individual's or group's internally held understanding of the external world (5, 6). Group mental models, which are the focus of this paper, represent the collective knowledge and understanding of a particular domain held by a specific population of individuals. Mental models are an empirical snapshot of the cognitive process that underpins human decision making and behavior. Mental models complement more traditional approaches to understanding environmental behavior by highlighting the interdependent relationships among attitudes, norms, values, and beliefs (17). For example, the Values-Beliefs-Norms model of environmental behavior hypothesizes a causal chain running from broad ecological values, to beliefs about environmental issues, to more specific behavioral norms. The network approach used here shows how these types of more general and specific concepts are linked together in a hierarchical and associative structure.

Mental models have evolved into an important area of research in environmental policy, risk perception, and decision making (18–20). A growing number of researchers are using mental models to better understand decision making in the context of

Significance

Sustainability is notoriously difficult to define and put into practice in the context of agricultural and other social-ecological systems. A crucial task within this debate is to analyze how practitioners understand the idea of sustainability. Using California winegrape growers as an example, this paper uses network science to describe the structure of farmer mental models of sustainable agriculture and link those models to behavioral aspects of sustainable agriculture. California growers have hierarchically organized mental models with more abstract goals in the center and more concrete strategies in the periphery. The concept of sustainability is a viable approach for linking knowledge to action; there are strong positive correlations between the sophistication of an individual's beliefs about sustainability, participation in local outreach programs, and adoption of sustainable practices.

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social-ecological systems (20). Two approaches that are especially relevant to this paper are Actors, Resources, Dynamics, and Interactions (ARDI) and Consensus Analysis (CA) (21). The ARDI approach uses participatory research methods to construct a group mental model of the interactions among stakeholders, resources, and ecological processes (22). The final product is a graphic conceptualization of how the group perceives the social-ecological system, its components, and their place in it, which can be used to inform management strategies.

The CA approach relies on similar data-collection techniques to elicit a group mental model that captures stakeholders' beliefs and values pertaining to how the social-ecological system should be managed and for what purpose (23). The mental models are then analyzed using quantitative methods to assess agreement among individuals and identify points for consensus. Along with addressing research questions about practitioner knowledge and decision making, both approaches have been used to facilitate multistakeholder management of social-ecological systems (21).

This paper conceptualizes group mental models as "concept networks" comprised of nodes representing unique concepts and ties representing associations among concepts. Network analysis methods are used to analyze the resulting relational structure of the mental model (24). The concept network approach is different from ARDI and CA in that network analysis methods (25–27) are used to analyze the structure of mental models and measure the importance of individual concepts based on their position in the concept network. This approach follows from Carley's work (6, 28), which is founded in the theoretical argument that human cognition operates in an associative manner (29). When a given concept is presented to the individual, memory is searched for that concept, ties between the concept and associated concepts are activated, and associated concepts are retrieved. The more associations a given concept has, the more likely the concept is to be recalled. Highly connected concepts serve as cognitive entry points for accessing a constellation of associated ideas.

We elicited our mental models from written text of farmers' definitions of sustainable agriculture, and follow Carley in arguing that written language can be taken as a symbolic expression of human knowledge (24). It is important to note that our mental models deviate from Carley's in that the associations among concepts are nondirectional and do not represent causality between concepts. Ties in our concept network represent concept co-occurrence, where two concepts occurred together in a single definition of sustainable agriculture. See *Methods* for more details.

Hypotheses. Hypothesis 1 is that mental models are hierarchically structured, with abstract concepts constraining the cognitive associations among more concrete concepts. For example, practitioners who define sustainability primarily as environmental responsibility versus economic viability may evaluate the benefits and costs of management practices with different criteria. This perspective is related to models of political belief systems where specific attitudes on public policy issues are predicted by general beliefs about policies and core values (29, 30). Construal-level theory also suggests that hierarchical belief-systems contain abstract, superordinate goals related to subordinate beliefs about actions needed to achieve them (31). The hierarchical structure reflects a basic principle of cognitive efficiency in taxonomic categorization (32), where more abstract concepts (e.g., bird) provide cognitive shortcuts to retrieve specific linked attributes (e.g., feathers, beak).

The concepts making up mental models of sustainability can be divided into two basic types, each with different levels of abstraction: goals and strategies (3, 33). Abstract goals are desirable properties, attributes, and characteristics of a sustainable system to be realized. Examples taken from this study include environmental responsibility, economic viability of the farm enterprise, continuation into the future, or soil health and fertility. Strategies are more concrete and include practices or approaches that are thought to contribute to the realization of abstract goals. Examples include cover cropping, water conservation, erosion control, integrated pest management, or organic certification. Although the level of abstraction might be conceptualized as a continuum, this simple categorization is useful for analysis. Another way of thinking about this categorization is that goals are value-driven outcomes of sustainability and strategies represent beliefs about the means to achieving those goals (34).

Hypothesis 2 is that mental models of sustainable agriculture will reflect geographic variation and local context. Differences in farmer knowledge and the practice of agriculture reflect regional biophysical and social differences (35). In particular, although abstract goals of sustainability are likely to be more universal across geographies, the concrete strategies used to achieve those goals may reflect geographical variation in terms of challenges and opportunities for realizing the goals (34). For example, achieving the goal of environmental responsibility in the Napa Valley requires water management and cover-crop strategies for reducing soil erosion by surface water runoff on steep hillsides. In Lodi, strategies for wind-born soil erosion control are more relevant across the gentle valley floor topography of the region.

Hypothesis 3 is that farmers who subscribe to more central concepts in the mental model are also more likely to engage in a range of sustainability behaviors. In particular, the sophistication of a farmer's definition of sustainability should be correlated with their participation in extension programs and adoption of sustainability practices. The extension programs in California viticulture explicitly train farmers in the idea of sustainability and also identify specific sustainability practices. Farmers who are motivated by sustainability are also likely to seek out these programs. Thus, participation, practices, and mental models represent a set of coevolving and synergistic processes.

Results

Farmer Mental Model of Sustainability and Its Hierarchical Organization. We constructed a mental model based on responses to surveys of winegrape growers in all three study regions. Using content analysis of farmers' self-reported definitions of sustainability (*Methods*), we classified 56 concepts into 19 (33%) abstract goals of sustainability and 37 (66%) more concrete strategies. We operationalized the mental model as a network where the concepts are nodes and valued ties represent the number of times two concepts co-occur together in a single definition of sustainable agriculture (*Methods*). We first identified an overall mental model by taking the union of the regional

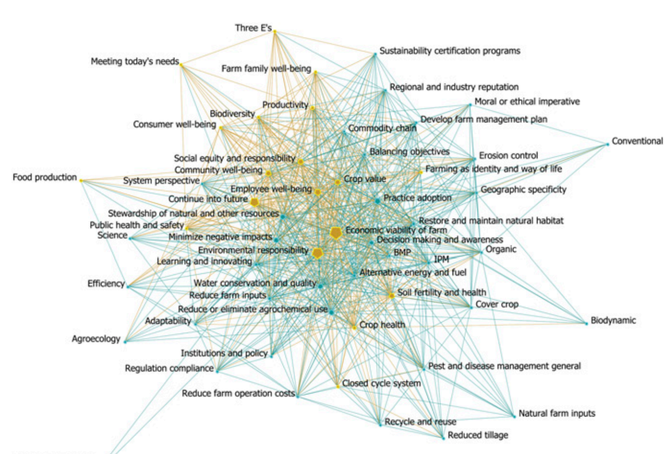

Fig. 1. Overall mental model of sustainable agriculture for California winegrape growers.

Table 1. Occurrence probability, centrality, and prominence

	Average occurrence/probability	Average network centrality	Average prominence
Goal	0.113	0.186	0.149
Strategy	0.045	0.050	0.050

concept networks. A union network is defined as the combination of nodes and ties from two or more networks (36). The union network provides a comprehensive picture of farmer thinking about sustainable agriculture.

The overall mental model from the union network is visualized in Fig. 1. Nodes are scaled by a measure of centrality we call "prominence," which indicates a concept's importance in the mental model. Prominent concepts are widely recognized among farmers as legitimate dimensions of sustainability and they are cognitively associated with many other central concepts. Technically, prominence combines the frequency that a concept appears in the network with its centrality (*Methods*). Because prominent concepts are linked to many other concepts, they are effective cognitive entry points for leveraging farmer thinking about sustainability. Ties are unscaled. Nodes are shaded by classification, with yellow-colored nodes representing goals of sustainable agriculture and aqua-colored nodes representing strategies. Table S1 lists all of the concepts, examples of coded text for each concept, classification as goal (G) or strategy (S), and three measures of centrality: prominence, occurrence probability, and eigenvector centrality. We chose the examples of coded text that best illustrate the core ideas of the concept.

The mental model was hierarchically structured where, on average, abstract goals were more central than concrete strategies. Table 1 shows that goals had higher occurrence probability and centrality, and were found to be three times more prominent in the mental model. Using whether a concept was a goal or strategy as a dichotomous dependent variable (37), prominence is a significant positive predictor in a combined logistic regression model as well as models for each region (Combined, $P = 0.032$; Central Coast, $P = 0.099$; Lodi, $P = 0.004$; and Napa Valley, $P = 0.038$).

Overall, the most central concepts in the mental model were abstract goals, including economic viability, environmental responsibility, and continuing into the future. These goals are commonly included in most definitions of sustainability. The next set of central concepts focuses on practices expected to achieve these goals, such as water conservation and reducing agrochemical use. Interestingly, the goal of social equity was less central in the mental model than some of the concepts related to economics and the environment.

Geographically Universal and Specific Aspects of Mental Models. We identified a geographically universal farmer mental model of sustainable agriculture by taking the intersection of the concept networks from each American viticultural area. An intersection network is defined as the subset of nodes and ties that are shared by all networks included in the analysis (6). In our case, the intersection network contains only the concepts that were present in definitions from all three regions. Table 2 reports the 32 concepts, their occurrence probability, network centrality, prominence, and classification as goal (G) or strategy (S). The universal

Table 2. Mental model concepts intersection

Concept (n = 32)	Occurrence probability	Network centrality	Prominence	Class
Economic viability of farm	0.185	0.916	0.550	G
Environmental responsibility	0.168	0.669	0.418	G
Continue into future	0.131	0.504	0.317	G
Crop value	0.051	0.248	0.149	G
Stewardship of natural and other resources	0.081	0.206	0.144	S
Community well-being	0.040	0.242	0.141	G
Employee well-being	0.044	0.232	0.138	G
Social equity and responsibility	0.037	0.215	0.126	G
Practice adoption	0.084	0.155	0.119	S
Water conservation and quality	0.098	0.140	0.119	S
Productivity	0.044	0.180	0.112	G
Soil fertility and health	0.064	0.156	0.110	G
Reduce or eliminate agrochemical use	0.098	0.107	0.103	S
Minimize negative impacts	0.057	0.142	0.100	S
Decision making and awareness	0.054	0.074	0.064	S
Balancing objectives	0.017	0.082	0.050	S
Restore and maintain natural habitat	0.034	0.059	0.046	S
Three Es	0.013	0.079	0.046	G
Farm family well-being	0.010	0.060	0.035	G
Biodiversity	0.017	0.043	0.030	G
Integrated pest management	0.044	0.012	0.028	S
Pest and disease management general	0.024	0.027	0.025	S
Crop health	0.034	0.017	0.025	G
Reduce farm inputs	0.034	0.014	0.024	S
Learning and innovating	0.017	0.028	0.022	S
Alternative energy and fuel	0.027	0.016	0.022	S
Organic	0.027	0.011	0.019	S
Cover crop	0.017	0.012	0.014	S
Efficiency	0.003	0.025	0.014	S
Adaptability	0.010	0.015	0.012	S
Reduce farm operation costs	0.017	0.003	0.010	S
System perspective	0.010	0.004	0.007	S

mental model contained 32 concepts, 13 (41%) of which were classified as goals and 19 (59%) as strategies.

We identified a geographically specific set of concepts by taking the difference of the concept networks from each of the three regions of study. In contrast to the intersection network, the difference is defined as the subset of nodes that are not shared by all networks included in the analysis (6). In other words, the difference includes some concepts that are only in two regions, and some concepts that are unique to a single region. The difference concepts represent geographically specific aspects of the farmer mental model of sustainable agriculture. Table 3 reports the difference concepts by American viticultural area. Concepts are ranked in decreasing order by regional prominence. Those concepts that were present in only one region—and are therefore geographically unique—are marked with an asterisk.

Consistent with our hypothesis, the ratio of goals to strategies was higher in the intersection (0.68) than in the difference (0.33). Among the 32 geographically universal concepts, 13 (41%) were goals and 19 (59%) were strategies. From the 24 geographically specific concepts, 6 (25%) were goals and 18 (75%) were strategies. However, a χ^2 test of whether there was statistical difference in the distribution of goals and strategies across each category was not significant [$\chi^2(1) = 1.495$, $P = 0.222$].

Qualitatively, the difference concepts do reflect some interesting geographically specific issues. For example, the strategy of "erosion control" appears in Napa Valley and Central Coast, where soil erosion is a problem because of steep topography and agricultural production on hillsides (38, 39). The concept of "sustainability certification" is prominent in both Napa and Lodi, regions where sustainable viticulture certification programs are fairly well-established (40). The "Lodi Rules for Sustainable Winegrowing" was established in the region in 2005, but emerged from a long history of research and engagement on Biologically Integrated Farming Systems and Integrated Pest Management (41).

Relationship Between Mental Models and Behavior. Our third hypothesis expects those farmers who included more central mental model concepts in their individual definitions of sustainability to be more likely to participate in extension activities and adopt sustainability practices. To measure an individual farmer's "sustainability cognition," we calculated the mean prominence value of all concepts included in their individual definition of sustainable agriculture. For example, if a given farmer's definition included the concepts of "crop value" (prominence = 0.165), "economic viability of farm" (prominence = 0.618), and "efficiency" (prominence = 0.014), the farmer's sustainability cognition measure would be 0.266 (the mean of the prominence measures). Farmers who mention more prominent concepts will have a higher measure of sustainability cognition.

For each region and California, Table 4 reports positive and statistically significant pairwise Pearson's correlation coefficients between sustainability cognition, participation in extension activities, and adoption of sustainable practices. It is important to emphasize that the correlations make no assumptions about causality: for example, whether participation in extension activities develops more sophisticated expressions of sustainability among farmers, or vice versa. Cross-sectional data of this type makes it difficult to identify whether any of these variables are causally before others. Although future research or more sophisticated models may identify a more explicit causal structure, we expect these variables to coevolve over time in a mutually reinforcing system of positive feedbacks.

Discussion

Our mental model analysis identified key concepts that are factored into a practitioner's decision-making process. The goals of economic viability, environmental responsibility, continuation into the future, and crop value are powerful drivers of decision making, with relevance across different social-ecological contexts. The hierarchical structure of the overall mental model suggests that although practitioners focus on achieving a common set of broad goals, the strategies they associate with realizing them are numerous and diverse. Key strategies include practice adoption, stewardship of resources, reduction or elimination of agrochemicals, and water conservation and quality enhancement. Because of their association with many other goals and strategies, central concepts are potential cognitive entry points for leveraging practitioner thinking about sustainability.

Debate About Definitions of Sustainability. Sustainability is notoriously difficult to define for the reason that it is a relative concept (42), which varies widely across space, time, and scale (43). Furthermore, diverse stakeholders often have divergent and even conflicting values and goals (44). Practitioners must grapple with the questions of what is to be sustained, for how long, for whose benefit, at what cost, over what geographical area, and measured

Table 3. Mental model concepts difference

Concept	Region prominence	Class
Central Coast		
Closed cycle system	0.125	G
Best management practices	0.112	S
Erosion control	0.068	S
*Recycle and reuse	0.060	S
*Meeting today's needs	0.048	G
Reduce tillage	0.048	S
Geographic specificity	0.046	S
Natural farm inputs	0.042	S
Science	0.036	S
Farming as identity and way of life	0.032	G
Consumer well-being	0.031	G
*Food production	0.031	G
*Conventional	0.029	S
Biodynamic	0.026	S
Regional and industry reputation	0.019	S
Develop farm management plan	0.016	S
Commodity chain	0.015	S
Regulation compliance	0.010	S
Lodi		
Sustainability certification programs	0.060	S
Science	0.012	S
Regulation compliance	0.053	S
Regional and industry reputation	0.077	S
*Public health and safety	0.135	G
*Institutions and policy	0.035	S
Farming as identity and way of life	0.116	G
Development farm management plan	0.046	S
*Cooperation among stakeholders	0.015	S
Consumer well-being	0.043	G
Commodity chain	0.053	S
*Agroecology	0.012	S
Napa Valley		
Sustainability certification programs	0.021	S
Reduce tillage	0.031	S
Natural farm inputs	0.017	S
*Moral and ethical imperative	0.029	S
Geographic specificity	0.016	S
Erosion control	0.039	S
Closed cycle system	0.035	G
BMP	0.039	S
Biodynamic	0.042	S

*Concepts that were present in only one region and are therefore geographically unique.

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Table 4. Correlation between sustainability cognition, participation in research and outreach activities, and adoption of sustainability practices

Region	Cognition, Pearson's r (n)	Participation, Pearson's r (n)	Adoption
California			
Cognition	—		
Participation	0.237* (272)	—	
Adoption	0.325* (292)	0.550* (723)	—
Lodi			
Cognition	—		
Participation	0.324* (86)	—	
Adoption	0.394* (87)	0.643* (209)	—
Central Coast			
Cognition	—		
Participation	0.271* (103)	—	
Adoption	0.330* (121)	0.450* (295)	—
Napa Valley			
Cognition	—		
Participation	0.302* (83)	—	
Adoption	0.247* (84)	0.614* (219)	—

*$P < 0.001$.

by what criteria (45). We argue that definitions of sustainability that are grounded in practitioners' viewpoints will have greater relevance to real-world contexts and therefore be more useful for guiding actions (46). Empirically measuring mental models of sustainability is crucial to know whether the normative ideas about sustainability discussed within academic, policy, and public circles are relevant to on-the-ground decisions.

Our study of mental models provided two main insights into practitioners' definitions of sustainability. First, mental models of sustainability are organized hierarchically along a continuum of abstractness from general goals of sustainability to concrete strategies for achieving those goals. At least among winegrape growers, the overall mental model is sophisticated and reflects many of the concepts discussed in the academic literature and among policymakers (47). Definitions that focus on central goals are likely to prompt practitioner thinking about their linked strategies, and are more likely to resonate with a greater number and diversity of practitioners. To the extent these goals and strategies are grounded in more general environmental values and norms, the network approach used here emphasizes the interdependent and relational aspects of sustainability thinking.

Second, more central abstract concepts are universal across geography, with only anecdotal evidence that strategies are customized to specific social-ecological contexts. This may be a feature of our study system because sustainability extension programs are advanced within California viticulture and winegrape-growing regions that (at least within California) have more similarities than differences. Mental models from social-ecological systems with more stark differences may show larger differences in how goals are linked to strategies. More research is needed to confirm or disconfirm the hypothesis that concrete strategies are more sensitive to geographic and other contextual variation.

Managing Knowledge Systems for Sustainability. Managing knowledge systems to link knowledge and action is a core goal in sustainability science (48). Knowledge systems include the institutional arrangements, organizations, and social networks that facilitate the transmission of knowledge among decision makers. Our results suggest that knowledge about sustainability, participation in extension programs, and practice adoption are mutually reinforcing processes.

In agriculture, local extension programs and partnerships have played a crucial role in managing knowledge systems (49). In the case of California viticulture specifically, there is a substantial body of literature demonstrating that these programs have had a positive influence on farmer adoption of sustainability practices (13, 50–53). The positive association we found between farmer sustainability cognition, participation in extension activities, and practice adoption indicates that knowledge systems do help expand practitioner understanding of social-ecological systems and influence their management behaviors. Extension programs can accelerate the development of knowledge and understanding about sustainability by clarifying the linkages among central sustainability goals and the associated strategies and practices for achieving them. An important component of this learning process may be the explicit use of the concept of sustainability, as it can serve as a heuristic for guiding practitioner decision making with a framework for balancing economic, ecological, and social costs and benefits. Thinking in terms of sustainability does track with behavior, and knowledge systems have the ability to support this process by providing opportunities for learning.

Methods

The following is a brief summary of the data collection and analysis methods; see *SI Methods* for specific details. The data were collected through a mail survey of winegrape growers delivered during 2011 and 2012. Survey delivery followed the Dillman method (54). A total of 822 completed surveys were returned for an overall response rate of 39.42% (55). Farmer definitions of sustainable agriculture were collected with an open-ended survey question that read, "Sustainable means different things to different people. How do you define sustainable agriculture? Please define sustainable agriculture in your own words." The survey collected a total of 297 usable definitions.

Based on these written responses, we used NVivo content analysis (56, 57) software to identify 56 unique concepts embedded in farmer definitions of sustainable agriculture. A random sample of 40 definitions was analyzed by multiple coders to establish the reliability of the content analysis framework. The coding process produced as a weighted, nondirectional (symmetrical) adjacency matrix. Nodes in the network represented concepts. Ties represented association between concepts. We defined association as co-occurrence of two given concepts in a single definition. The value of ties represented the number of definitions in which the two concepts co-occurred. For example, the concept of "productivity" occurred in a total of 22 definitions. The concept of "continue into future" occurred in a total of 162 definitions. The two concepts occurred together in the same definition a total of 16 times. Therefore, the value of the weighted tie between "productivity" and "continue into future" was 16.

We collected individual-level data on two measures of farmer behavior: sustainability practice adoption and participation in extension activities. The first measure was the percentage of sustainability practices farmers reported having adopted from a list of 44 practices included in regional sustainable viticulture workbooks. The second variable was the total number of extension activities survey respondents reported having participated in within the past 5 years. The activities included field meetings, classroom-style meetings, organization newsletters, organization staff communication, extension program internet resources, sustainable viticulture certification, sustainable viticulture self-assessment, and regional and state-wide viticulture industry fairs (10–12).

We measured the centrality of concepts in the mental model in three different ways: occurrence probability, network centrality, and prominence. Occurrence probability was calculated as the ratio of definitions that included the given concept to total definitions in the sample. Network centrality is the degree to which a concept is associated with other concepts in the network, and was calculated using Eigenvector centrality (58), taking into consideration tie weights (59). Prominence indicates a concept's influence in the mental model, taking into account both frequency of occurrence and centrality. Because both scores ranged between zero and one, the average is a valid measure. From a measurement standpoint, prominence is analogous to combining survey responses into a single scale to measure a latent variable.

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