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Research, part of a Special Feature on Convergent Science for Sustainable Regional Systems

Fuzzy SETS: acknowledging multiple membership of elements within social-ecological-technological systems (SETS) theory

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ABSTRACT. Convergent research to tackle complex, wicked problems requires synthesis across multiple sectors and disciplines, but epistemological, ontological, and linguistical disagreements between disciplinarily diverse research teams can hinder the progress of transdisciplinary team efforts. For example, in social-ecological-technological systems (SETS), elements within the system may require distinction between component (S-E-T) parts to be conceptualized and modeled. Current SETS literature has focused predominantly on the deep interconnections across these social, ecological, and technological elements, but has not addressed how to explicitly acknowledge potentially messy, multi-membership classifications of elements within these categories. We introduce the conceptual framework of Fuzzy SETS, drawing on mathematical fuzzy set theory and SETS literature. By treating these categories as "fuzzy," or being capable of multiple memberships, we investigate how the conceptual framework of fuzzy SETS can facilitate convergent, collaborative research across multiple disciplines and epistemologies by explicitly acknowledging and visualizing differences and similarities in perception of a given SETS. We apply this framework to our own work of creating a system dynamics model of the Santa Fe Watershed, New Mexico. Within our network of researchers, diverse perspectives exist when categorizing elements within the Santa Fe Watershed into social, ecological, and technological categories. Our findings support the hypothesis that the fuzzy SETS conceptual framework is a way to honor a diversity of epistemological perspectives within transdisciplinary teams by explicitly accepting that different views can coexist and can actually enrich our understanding of systems by creating a basis for asking deeper questions regarding their elements and dynamics.

Key Words: *collaborative modeling; fuzzy SETS; social-ecological-technological systems, SETS; system dynamics modeling; team readiness*

INTRODUCTION

Bridging existing disciplinary divides is imperative for facing pressing wicked problems: complex, multidisciplinary problems, such as managing water resources in a changing climate, cannot be addressed within the bounds of one discipline (Chettiparamb 2007, DeFries and Nagendra 2017). Major efforts by the United States (US) National Science Foundation (NSF), e.g., NSF's "10 Big Ideas," including "Growing Convergence" (NSF 2018), and the National Socio-Environmental Synthesis Center (SESYNC 2023, https://www.sesync.org/) highlight the urgent need to bridge multidisciplinary divides and to provide much needed synthesis among disciplines. Convergence research is defined by the NSF as research driven by a specific compelling problem that requires deep integration across disciplines (NSF 2018).

Effectively engaging in highly interdisciplinary, convergent research that seeks to synthesize knowledge is challenging because of different disciplinary cultures, measures of success, and timelines, and effective interdisciplinary engagement requires clear communication and mutual understanding within the team (Eigenbrode et al. 2007, Lynch et al. 2015). Convergence is even more difficult when there is limited or no shared language and epistemology, or if groups do not start from a place of acknowledging these differences and lack of a shared platform (Morgan et al. 2025). Chambers et al. (2022) found that diversity within teams, without the presence of intentional facilitation, tends to close debate rather than open those conversations up to mutual learning and respect, thereby exacerbating existing tensions and power imbalances. In addition, people from different disciplines, marked by different epistemologies and ontologies, may fail to communicate effectively within a framework that requires distinct classifications. This failure of communication then presents a challenge in synthesizing multi-, inter-, and/or transdisciplinary work. This observation is informed both by the co-authors' collective experiences in collaborative interdisciplinary research settings and relevant literature (e.g., Lynch et al. 2015). However, diverse perspectives and diverse framings are necessary to advance our collective understanding of complex systems (Peek et al. 2020, Chester et al. 2023, Morgan et al. 2025).

Elements, defined as the individual component parts, within social-ecological-technological systems (SETS) are deeply interconnected across SETS categories (social, ecological, and technological; Grimm et al. 2017, Markolf et al. 2018, McPhearson et al. 2022). Often, there is also utility and necessity to categorize elements and organize ideas, especially when considering large, complex systems (Papachristou and Rosas-Casals 2016). We define a system as an interconnected collection of elements that can change over time (Meadows 2008). In a SETS framework, these elements are often described across social, ecological, and/or technological categories. In comparison to a social-ecological systems (SES) framework, a SETS framework emphasizes the critical role of technology and built infrastructure within human activities and ecosystem processes (McPhearson et

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al. 2016). By zooming in to specific subsystems within the SETS system, researchers may find utility in having more focused and constrained conversations, models, and analysis (Webster et al. 2025). Due to their inherent interconnections, some elements do not fit neatly into predetermined categories and exist either on the boundary of multiple categories or are even key elements within multiple categories.

Although previous scholarship in SES and SETS has focused on the interconnectedness of the systems and the need to analyze these as deeply coupled systems (e.g., Markolf et al. 2018, Grimm et al. 2017, McPhearson et al. 2022), we focus on the membership of elements themselves, e.g., elements such as social capital, ecosystem services, and forest management, identified in Figure 1 and Table A1.1 through the process described in Box 1, and these elements' categorization as part of social systems, ecological systems, and/or technological systems, and specifically explores the fluidity of the boundaries between these categories. The concept of element membership within a system has been only briefly discussed in current literature. For example, in Markolf et al. (2018), the authors write:

> *When analyzing and discussing SETS, we acknowledge that social, ecological, and technological components do not always fit neatly into distinct, decoupled classifications.*

We note that the term "component" in Markolf et al. is comparable to the term "element" in our study. Similarly, in Morgan et al. (2014), on considering the categorization of a dam within a water resource system, they write:

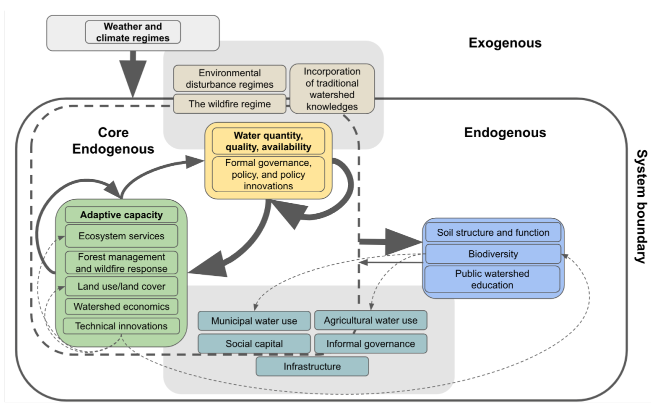
> *it can be difficult to parse the "social" from the "ecological," as they often co-emerge and intertwine.*

In both examples, this challenge of classification is acknowledged without offering additional guidance on actually managing this lack of ease in categorizing system elements.

The difficulty of categorizing elements to create a conceptual or quantitative SETS model is further complicated when working in large, multi-, inter-, or transdisciplinary teams in which team members may not come from a place of shared definitions, epistemology, or ontology (Morgan et al. 2025, Webster et al. 2025). Previous systems literature has looked at the benefits and challenges of integrating diverse knowledge domains from a systems thinking perspective. However, most systems literature assumes an agreed-upon identification for system elements among scientists/researchers yet does not investigate different opinions within the group (e.g., Gray et al. 2012, Hansson and Polk 2018).

Because current SETS literature does not address how to explicitly acknowledge multi-membership classifications, we seek to offer a new fuzzy social-ecological-technological systems (fuzzy SETS) conceptual framework to work with the reality of multi-membership elements across SETS. Fuzzy SETS draw on fuzzy sets theory and applies these concepts to a systems setting. In mathematics, fuzzy sets theory is applied in cases where mathematical sets (collections of mathematical elements) have elements with multiple degrees of membership (Zadeh 1965, Prokopowicz et al. 2017). A classical, or "crisp" set has firm membership boundaries (Prokopowicz et al. 2017). In a crisp set context, an element would be either a social, an ecological, or a technological member within the SETS framework. However, there may be uncertainty about the element's membership. For example, within a crisp framework, we can only describe that there is a 50% probability that an element is social or a 50% probability that it is ecological, but its "true" membership must be defined entirely in one category. A fuzzy set, in contrast, allows for multiple memberships of an object within different groups (Zadeh 1965, Prokopowicz et al. 2017), rather than only describing the uncertainty of the observer's information, or describing the intrinsic randomness of a system element (i.e., epistemic and aleatoric uncertainty, respectively). In the fuzzy set framing, a single element could be described as both 50% social and 50% ecological in membership and categorization. We propose fuzzy SETS as a way to integrate fuzzy set theory concepts into SETS theory to embrace the possibility of elements' multiple memberships across the three categories of social, ecological, and technological, which are inherent in SETS.

Fig. 1. Resulting coarse-scale model from the Santa Fe River Watershed, displaying the relationship between the elements used for the fuzzy SETS study, described in Table 1 and in Appendix 1, Table A.1. Element types are classified based on relative influence and dependence on other elements; these element types are denoted by color. Element types shown in this figure, by color: environmental elements outside of the system boundary (light grey) are elements that conditions the system and cannot be controlled; target elements (green) are elements that are more dependent than influential, but can influence the system if guided through strong action; stake elements (yellow) are potential "breakpoints" due to simultaneous influence and dependence within the system; exit elements (blue) indicate outcomes or results of system dynamics; remaining elements in the gray boxes (teal, tan) had high ambiguity in the model classification process and are positioned in this figure based on relevance and connectivity to other elements. Bolded elements indicate relatively high confidence in the element type. The weight and direction of arrows correspond to the level and direction of influence of element types. Dashed lines indicate important indirect relationships that were identified from the structural analysis (cross-impact matrix multiplication analysis; MICMAC). For a full description of the process to create this coarse-scale model, and of the model itself, see Webster et al. (2025). Figure 1 also appears in Webster et al. (2025).



In this study, we focused on the following research questions:

(1) How do perceptions of individual system element membership (s) in social, ecological, or technological categories vary across a group of scholars across diverse areas of expertise?

(2) How can the proposed conceptual framing of fuzzy SETS help acknowledge gaps between different disciplines (e.g., epistemological, linguistical differences) and give multidisciplinary teams a tool to map their similarities and differences for research moving forward?

We hypothesized that the fuzzy SETS conceptual framework is a way to honor a diversity of epistemological perspectives by explicitly accepting that different views can coexist and can actually enrich our understanding of systems and create a basis for asking deeper questions regarding their elements and dynamics. We draw on structured techniques in dialogue and use conceptual models for communication, which have been previously implemented to overcome some of the challenges associated with highly interdisciplinary and collaborative research (Heemskerk et al. 2003, Eigenbrode et al. 2007, McDonald et al. 2024).

This study provides two key advancements for convergent, collaborative teams to achieve deep integration across disciplines. First, fuzzy SETS provide a conceptual framework for teams to represent and simultaneously hold a variety of epistemological perspectives, which is critical to productive, ongoing convergent research (Morgan et al. 2025). Second, this study proposes and exercises a three-step process to apply fuzzy SETS, by which teams can identify both commonalities and differences through structured activities as they build functioning conceptual models to understand the systems in which they are working as teams (Webster et al. 2025).

The concept of fuzzy SETS grew from conversations among the coauthors, who worked on building a system dynamics model of the Santa Fe River Watershed together (see Webster et al. 2025). The Santa Fe River Watershed (Box 1) is selected as our case study of a complex system because it is emblematic of a Western United States watershed faced with multiple challenges and opportunities that can be investigated through a SETS framework, including drought, wildfire, contamination, flash flooding, and a growing population (Webster et al. 2025). To investigate our research questions about fuzzy SETS, we draw on our collective experience from building this conceptual model together (see Figure 1 and Box 1). This system dynamics model was catalyzed by a workshop (January-February 2022) focused on modeling the SETS within and related to the Santa Fe River Watershed, which is located in the state of New Mexico, USA, and described in detail in Webster et al. (2025). A brief summary of the workshop and the resulting conceptual model of the watershed system is provided in Box 1.

FUZZY SETS CONCEPTUAL FRAMEWORK

We propose a new fuzzy SETS conceptual framework to explicitly account for multiple membership of elements (also referred to as variables in some systems' literature) across social, ecological, and technological categories (and related elements). In a fuzzy SETS conceptual framework, drawing from principles of fuzzy logic, a single element can have anywhere from no membership to partial membership to full membership in a given category, and categories are not mutually exclusive. We visualized this concept through the fuzzy SETS diagram, a ternary plot with each vertex of the triangle representing one of the three categories: social (depicted as the bottom left vertex in the color red), ecological (depicted as the top vertex in the color blue), and technological (depicted as the bottom right vertex in the color yellow; Fig. 2). Elements within the system can then be plotted on the fuzzy SETS diagram to clearly visualize the fuzziness of their membership.

Box 1:

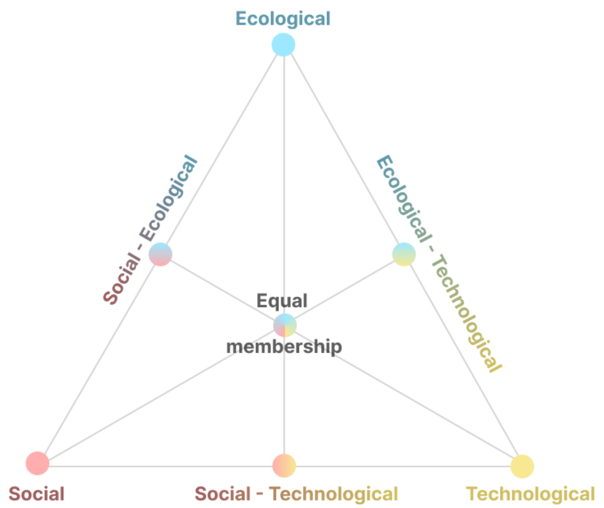
Santa Fe River Watershed: workshop and conceptual model

The Santa Fe River Watershed System Dynamics Workshop (January-February 2022) brought together 28 researchers from a wide range of disciplines and levels of expertise to learn about system dynamics modeling, hypothesize dynamics in the Santa Fe Watershed, and model those dynamics. The workshop applied the collaborative, adaptive, and multiscale (CAMS) system thinking framework, described in Webster et al. (2025). Participants' primary academic disciplines included biology, economics, geoscience, law, education, engineering, geography, health sciences, journalism, communications, planning, hydrology, agronomy, social psychology, and policy. During the workshop, teams classified elements as stocks and flows and began building system dynamics models around their research questions. This resulted in an initial list of 293 system elements that were later synthesized into 21 elements through a card-sort activity and resulted in the coarse-scale model shown in this box. These elements are the same list of elements used for the fuzzy SETS activities and discussion. We note that the final coarse-scale model (see Fig. 1) combined two elements such that the final coarse-scale model had only 20 elements.

The geographic bounds of the Santa Fe Watershed in New Mexico, USA, as considered in our study, are generally the topographic and hydrologic boundaries of the Santa Fe Watershed from its headwaters to its confluence with the Rio Grande. We treated this as a soft boundary, and included lands, waters, people, and infrastructure that extended beyond this boundary that were significant to the management of water in the Santa Fe Watershed. The Santa Fe River Watershed was chosen as our case study as a complex system because it is emblematic of the need to adapt water resource management to increasing water scarcity and heightened risk of disruption from climate-related disasters in the Western United States. For a complete description of the Santa Fe River Watershed Workshop and more background on the watershed itself, see Webster et al. (2025).

A ternary plot, also known as a Gibbs Triangle, or a triangle plot, can show the ratios of three elements on an equilateral triangle (Hamilton and Ferry 2018). A ternary plot is particularly useful for depicting three elements on a two-dimensional plot and thus avoids the need for a 3-D visual, which can be difficult to interpret on a 2-D surface (Tufte 2001). Although this is a common diagram to describe soil texture, rock composition, geochemical and chemical composition, and other applications spanning the physical sciences to economics, the ternary plot with a focus on

Fig. 2. Fuzzy SETS diagram to visualize the multiple membership of elements within systems. Points located on any vertice of the triangle indicate that the element only has membership within that single category. Points located at the midpoint of each leg of the triangle indicate that they have equal membership in the two categories at the end points of that leg, but no membership in the category of the third vertex of the triangle. Elements equidistant from all vertices, marked as "equal membership" with a gradient of all three category colors, indicate equal membership in each of the three social, ecological, and technological categories.



the interior of the triangle, rather than just the vertices, is relatively new to the SETS literature. The first known published instance of this ternary plot to describe SETS appears in McPhearson et al. (2022) and focuses on considering hypothetical levels of interaction in urban SETS. In contrast, our study focuses on visualizing team members' diverse perceptions of element membership within SETS as a means for team formation and collective understanding. Other known visualizations that have been employed to communicate similar messages have primarily been in the form of a Venn diagram (e.g., Fig. 1 in Feagan et al. 2023). As such, the fuzzy SETS framework is the first known instance of applying a ternary plot to describe element membership within a SETS framework for teams to work toward a transdisciplinary and/or convergence research framework. The advantage of a ternary plot over the existing, more-common Venn diagram is the ability to better quantify membership levels among the different categories, rather than being a binary (member/not member) assignment. We note that although the above ideas were developed independently from one another, the Santa Fe Collaborative Workshop (Webster et al. 2025), on which this work is based, took place prior to the publication of McPhearson et al. (2022). We identify that it is significant to see two groups of researchers exploring the gradient of the interior of a triangle within a SETS framework at similar points in time, in different but related ways.

Though the ternary plot is commonly used in some fields, since it is relatively new to SETS, we describe three key types of points and their interpretation within the fuzzy SETS diagram.

- Elements at a vertex of the triangle: points located on any vertex of the triangle indicate that the element only has membership within that single category. For example, if an element were to be plotted where the blue dot at the ecological vertex is located, it would indicate no (0%) membership in social or technological categories.
- Elements at the midpoint of each leg: points located at the midpoint of each leg of the triangle indicate that they have equal membership in the two categories at the end points of that leg, but no membership in the category of the third vertex of the triangle. For example, the social-ecological midpoint (half red and half blue circle) indicates equal membership between the social and ecological categories, and no membership in the technological category.
- Elements at the center point of the triangle: elements equidistant from all vertices, marked in Figure 2 as equal membership, with a gradient of all three category colors, indicate equal membership in each of the three social, ecological, and technological categories.

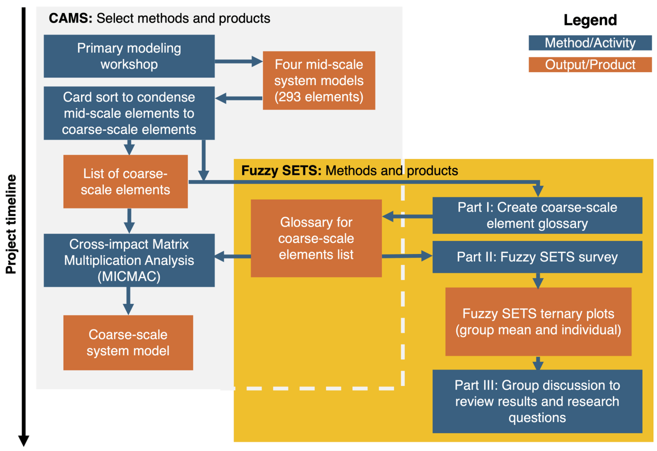
One limitation of the ternary plot is that this visualization cannot distinguish between absolute values of membership across the three categories; it can only visually distinguish relative values between the categories. For example, if an element is rated as having equally partial membership in all three categories, or whether it is rated as a full member of all three categories, the element will be depicted in the same location (at the center point of the triangle).

Rather than requiring consensus or neat categorization of elements, a fuzzy SETS framework allows explicitly for the messy multi-membership condition. As an alternative to treating multi-membership as exception, our fuzzy SETS framework embraces the plurality of element membership as an inherent part of SETS.

METHODS

As an initial step toward understanding the potential role of fuzzy SETS within collaborative, interdisciplinary research, we designed a series of self-reflexive exercises to synthesize our group's diverse perspectives when categorizing elements within a system dynamics model. Self-reflexivity is defined as the process of abstracting our own thought processes and behaviors without actively producing them, which is a merit associated with interdisciplinarity (Arnold et al. 2023). We note that this could be applied beyond a system dynamics setting and is intended to be applicable to research broadly related to SETS and related elements. The exercise is divided into three parts: (1) co-creating a shared glossary of identified elements, (2) classifying membership for each element in each of the three (social, ecological, and technological) categories, and (3) engaging in a guided self-reflexive group discussion on results from the classification activity. Identified relevant elements were the result of a group workshop, described in detail by Webster et al. (2025). A subset of participants from that initial workshop continued as part of this present study, which extended beyond the timeframe and scope of the initial workshop. The relationship between the companion paper, Webster et al. (2025), and the present study, is illustrated in Figure 3.

Fig. 3. Methods and key products in this study, and the relationship to the companion study on collaborative, adaptive, and multiscale systems (CAMS; Webster et al. 2025).



Part 1: co-creating a shared glossary for identified relevant elements

We first identified the system (the Santa Fe River Watershed) and relevant system elements through a collaborative, adaptive, and multiscale system thinking framework (CAMS) described in Webster et al. (2025) and in Box 1. Through the CAMS framework, we synthesized the 293 mid-scale elements (elements used within four system dynamics models created through the workshop) into 21 coarse-scale elements (elements that are part of systems thinking models related to major themes and interrelationships; see Table A1.1), for consideration in this fuzzy SETS study (Webster et al. 2025).

With this synthesized set of 21 elements, we identified explicit definitions for each element and invited feedback and revision for the initial definitions and citations. After seeking input from the collective coauthor team, we finalized the element definitions in a glossary made available to the coauthor team for the following two exercises (Parts 2 and 3). The full element name, abbreviated element name, resulting glossary, and accompanying citations are included in Appendix 1, Table A1.1. We note that Part 1 is not strictly required for the application of fuzzy SETS within the defined visual framework but is a critical part of the methodology that the team used in this study.

Part 2: individual classification activity

The second part of the exercise was a survey completed individually whereby each researcher characterized each of the system elements through the fuzzy SETS framework. Before completing the membership section, each researcher was asked to self-identify within a primary social, ecological, or technological expertise, then define the three terms (i.e., social, ecological, and technological) according to their own discipline or personal understanding. Before starting the fuzzy SETS categorization portion of the survey, researchers were asked to put on their "disciplinary hat," that is, to think as they have been trained within their discipline, and assign the strength of membership of an element among 3 categories (social, ecological, and technological) from 0 (no membership) to 10 (full membership; see Figure A2.1 and Question 7 in Table A2.1). For any given element and/or category, the researcher had the option to respond "I don't know" rather than assign a number, and every Likert-scale question was accompanied by a free-response question to express any clarification or nuance. For each element, individuals were invited to share their thoughts on any of the membership levels that they indicated (Question 8, Table A2.1). A digital platform was favored to allow for maximum flexibility and inclusion, given the realities of scheduling a group of this size (11 researchers who participated in Part 2). Designing this activity as an individual, asynchronous exercise was preferred to allow individuals to think at their own pace through each question and not be influenced by potential questions or comments by others.

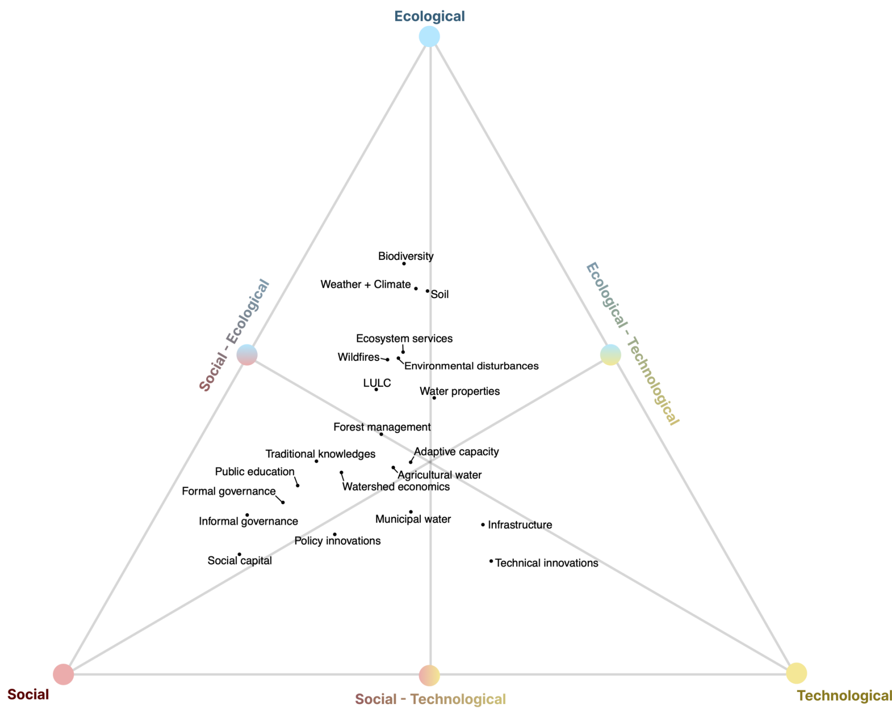
After the survey was completed by the coauthor team (Fig. 4), results were visualized in R using the "ggtern" package (Hamilton and Ferry 2018). Results are visualized for the mean response for each element together on one SETS diagram (Fig. 5), as well as for each element with each individual response depicted by discipline family (social science/humanities, physical/natural sciences, or technology/engineering; Fig. 6).

Fig. 4. Summary of researchers who completed Part 2 of the self-reflexive exercise. Each dot represents a researcher. Color represents their self-identified expertise (red as Social; blue as Ecological; yellow as Technological).

Part 3: group self-reflection activity

The third part of the exercise was to engage in a post-survey group reflection. This reflection was organized as a group discussion, with live and virtual options, to look at the spread of our 21 elements across the fuzzy SETS spectrum. We first reviewed the steps leading up to these results, including the conceptualization of fuzzy SETS from previous discussions, as well as the two steps (collaborative glossary building and the individual classification activity) completed up to this point. We then presented the overall results and gave an overview of how to interpret the results. Everyone individually explored the results for approximately 10 minutes before engaging in a group discussion. For the group discussion, we started by sharing overall reflections of the exercise, i.e., how we felt when completing the activity, what was challenging, and what felt surprising about the results. Based on group interest, we then selected specific elements to discuss in depth. We finished the reflection by relating the results we had discussed back to our two research questions. As with all of our meetings as a group, the meeting was recorded via Zoom (a digital conferencing application) to capture the conversation.

Fig. 5. Aggregated results (average ratings for each element). Full element names, matched with element abbreviations, are provided in Appendix 1 in Table A1.1.



RESULTS AND DISCUSSION

Across the 11 respondents from the self-reflexive individual exercise, we represent 6 academic departments (see Fig. 4). We use researchers' primary academic department as a proxy for discipline. The departments, in alphabetical order, include: Biology; Civil, Construction, and Environmental Engineering (CCEE); Community and Regional Planning (CRP); Earth and Planetary Science (EPS); Geography and Environmental Studies (GES); and Public Administration. Among these researchers, 3 identified primarily in the social sciences/humanities; 5 identified primarily in the physical/natural sciences, and 3 identified primarily in technology/engineering. We note that the self-identified expertise did not always align with the typical disciplinary or department expertise: for example, one of the GES researchers identified as technological rather than social, while one of the CCEE researchers identified their expertise as ecological rather than technological.

Before rating levels of membership of every element within each category, individuals provided a definition for each category. This was done for two reasons: to help situate each researcher before answering the remainder of the survey, and to acknowledge that there may be diverse definitions for social, technological, and ecological within the group.

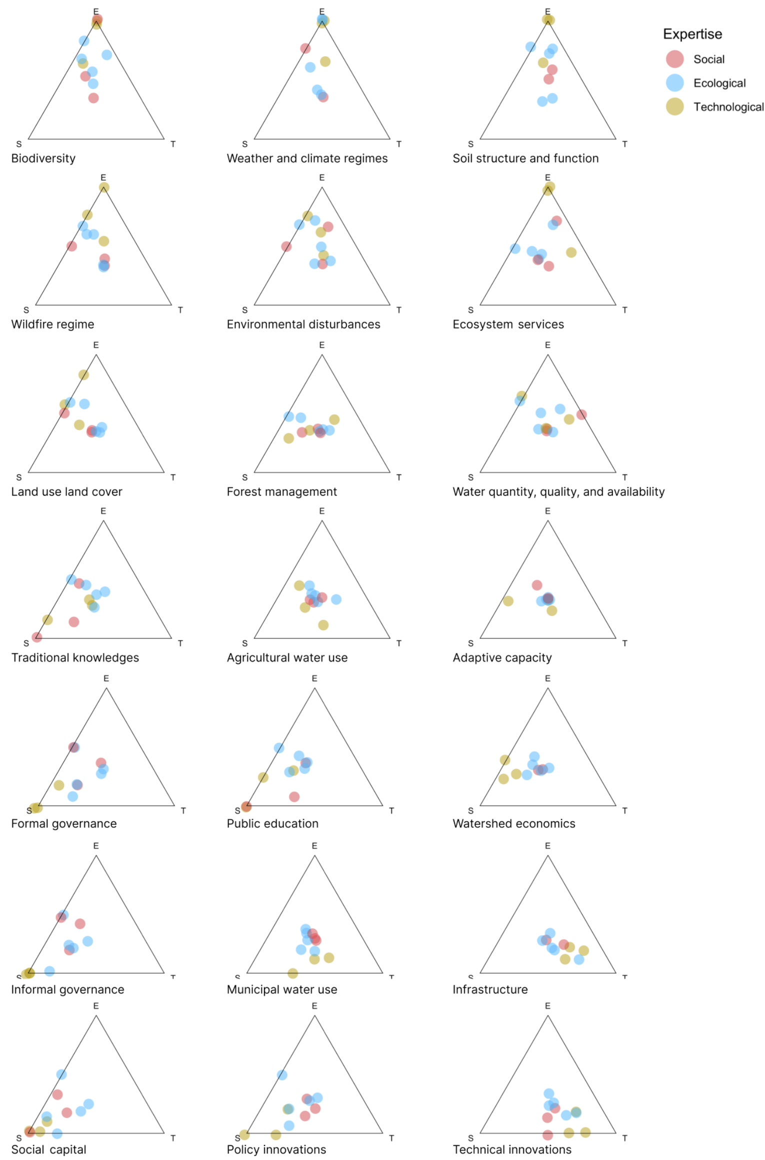
Definitions for the social category ranged from very broad (e.g., involving people) to more specific aspects, such as a focus on interactions between people (e.g., related to society, groups, and community, having to do with human interactions, interaction of people), or a focus on particular products of people and their interactions (e.g., ideas and methods that cannot be understood outside of their affiliation with humans, or economics, culture, politics, and values). Two definitions within the social category responses focused on the social category as nested within the ecological category (e.g., a subset of the ecological domain... and human components of an ecosystem...).

Definitions of the ecological category also ranged, with some definitions focusing on purely natural or relatively unmanaged biological systems, exclusive of humans, while others explicitly included humans (e.g., all relationships between living organisms, including humans). Some definitions used more precise language (e.g., biotic and abiotic components) while others used more general terms (e.g., the environment or surroundings).

Definitions of the technological category were more consistent in their definitions existing in relation to one or both of the other categories. Some examples include: pertaining to the manipulation of natural or artificial systems, systems devised by humans as they interact with the physical environment, and technology that impacts people and the natural environment, for better or for worse. A few definitions focused on defining technology through its utility (e.g., forms of decision support, means through which people better understand or control our world). Although one definition focused on a skeptical role of technology (e.g., as noted by including "for better or for worse," at the end of the definition), other definitions implied that technology had positive purposes: improving performance, benefiting humans, and solving problems.

In post-survey conversations when the researcher group gathered to discuss results, these definitions were often referred to when

Fig. 6. Individual researcher results for each element. Elements are arranged in relative position to an element's mean position in Figure 5, i.e., the "most" social element is correspondingly placed on the bottom left of this figure (social capital).



describing why someone might have categorized a particular element in one way rather than another way. Similar to the function of the element definition table, this provided a way to better understand others' perspectives, rather than assume there is only one definition for these complex topics.

Results from the classification exercise are shown in aggregate (mean values) in Figure 5, while individual responses, color-coded by researcher expertise, are presented in Figure 6.

Key findings

1. When people (either individually or as a group) categorize fuzzy SETS elements, the exercise is challenging but insightful to prepare teams for convergent research. On the whole, our group of researchers expressed that the exercise of determining membership levels for a given set of elements was challenging and ultimately insightful. One challenge shared among researchers was paralysis of putting any one element into any one category bin, i.e., many experienced that the more they thought deeply about any single element, even if it had a seemingly obvious category, the more they realized that the element had membership across all categories. This was especially the case for the technologically inclined elements, for which there were not purely technological elements. The structured opportunity to engage critically with the elements and consider cross-boundary perspectives also facilitated discussions that challenged disciplinary norms and supported communication about these norms, which led to collaborative team insights.

Through a conceptual fuzzy SETS framework that embraces plurality, and by welcoming discussion that challenges typical disciplinary norms and acknowledges differences (especially differences that may emerge from positivist and constructivist approaches as discussed in Morgan et al. 2025), we demonstrate how fuzzy SETS can specifically facilitate increased involvement from the social sciences and humanities within teams that aim to engage in convergent research.

2. The presented fuzzy SETS three-part method can provide opportunities to share different views and build a foundation for shared definitions: The need for common definitions, with citations, was highlighted as a need for convergent teams to work together. In the discussion after the session, there were repeated expressions of gratitude for the shared glossary (Table A1.1), both for providing a source of shared definitions, but also for the collaborative process through which it was made. Although the exercises provided the opportunity to co-create a set of shared definitions, this also provided the opportunity to share differing frames of reference when interpreting the categories of social, ecological, and technological. For example, this provided an opportunity for one coauthor to share that from their perspective, rather than seeing SETS as three parallel categories, they defined technological to exist as a subset of the social category, and the social category is then nested within the ecological category. Notably, the fuzzy SETS framework, as set up by the Part 2 survey, was flexible enough to capture this distinction: every element could be assigned a full score of 10 in ecological, with varying levels of membership for social and technological. The visual result of this definition is that an element would never be placed in the T corner of the ternary plot. We note that Finding 2 is a direct outcome of Part 1 of the methods from this study, but that it is not strictly required to engage with Part 2 or Part 3 (e.g., if a glossary was already created).

3. Fuzzy SETS, conceptually and through the three-part method, can help teams identify common ground from which to build convergent research. In reviewing Figures 5 and 6, the group was surprised to see how central all the elements were, on average. Looking at the aggregated results in combination with the individual results by visual inspection, it is clear that nearly all the elements had responses that were placed near the center of the triangle. Some of this was by extension of the definitions that an individual had created for each of the categories: for example, for those who view technological only in relation to social and ecological, it is clear within that framework that any given element considered to have membership in technological must also have at least some membership in social and ecological. Interestingly, although there were at least a few individual responses that were categorized as 100% belonging to either ecological (i.e., biodiversity, weather and climate regimes, soil structure and function, wildfire regime, and ecosystem services) or social (traditional knowledges, formal governance, informal governance, public education, social capital, policy innovations), there were no responses that categorized any element as purely technological, with technical innovations and infrastructure coming closest but not entirely at the technological vertex. One observation after considering these results was that there were also fewer technological elements included in this case study, which perhaps represents a bias of the researchers included in the study because they self-identified which elements would or would not be included in this study. Overall, the group felt surprised there were not more obvious differences between results, and although there were variations within each element, the exercise provided more opportunity to discover common ground than expected. This identified common ground emerged from the fuzzy nature of the elements that the fuzzy SETS conceptual framework explicitly allows, in contrast to traditional or crisp SETS. By allowing for diverse perspectives to coexist and be visually represented together within the same conceptual framework, fuzzy SETS opened opportunities for listening and sharing, rather than creating competition or forcing consensus for which perspective would be adopted by the team moving forward. The common ground allowed for trust to build between researchers across methodological and epistemological backgrounds, which is a required basis for convergent research (Morgan et al. 2025).

Revisiting the research questions

What differences may exist across diverse disciplinary expertise when perceiving membership in social, ecological, or technological categories within SETS? Relatively few responses placed any elements as purely social or ecological, and there were no responses for elements that classified any element as purely technological. However, of the 22 responses (out of the 231 total responses across the 11 researchers and 21 elements) that were placed entirely on one vertex of the triangle (i.e., classifying an element as having membership in only one category in Figure 6), 16 of these responses were from individuals who identified as having expertise in the technological sphere. This result led to a discussion and self-reflection among those researchers on how the academic training they received may encourage a higher comfort level and requirement to categorize elements more narrowly rather than in fuzzy ways. The prompt of the survey asked the group to wear their disciplinary hat and consider the following questions in a way that is emblematic of their training within their discipline. We note that this is not necessarily how the individual researcher would classify each element from their own perspective, especially because many of the researchers identify as inter- or trans-disciplinary scholars, and we acknowledge that the specific results of responses within the ternary diagram is likely to be unique to the context of this specific project and group of researchers.

Our next question focused on the conceptual framing of fuzzy SETS and whether it could help acknowledge the gap between different disciplines and give multidisciplinary teams a tool to map their similarities and differences for research moving forward. As a direct outcome of the first research question through the discussions that followed the survey, we identified fuzzy SETS (as a concept and in the associated three exercises) as an effective tool in prompting meaningful conversation that can help identify disciplinary differences within a specific group of researchers. The group identified many future opportunities for the conceptual framing of fuzzy SETS to help multidisciplinary teams work together more effectively by both acknowledging those differences and identifying shared perspectives. The mean-value plot (Fig. 5) was identified as a possible consensus building tool, i.e., a visual way to discuss elements. Both plots (Figs 5 and 6) provide a platform to discuss why each element is placed at each location and nominally agree to both definition and placement, while still honoring the diversity in perceptions within the group. At the same time, there was concern for oversimplifying the team's knowledge into only the S-E-T categories, which some felt were too broad, but this was a critique more of SETS in general rather than the focus of this paper. We found that the conceptual framing of fuzzy SETS allowed for the coexistence of different views that enriched our understanding of the case study system, and created a nuanced, fuzzy basis for asking deeper questions regarding the system elements and dynamics.

Overall, there was strong consensus that being able to have these conversations as a group takes labor, from creating the shared glossary to engaging in these exercises, but was necessary for understanding complex systems from an inter-, multi-, or trans-disciplinary perspective. When to implement these specific fuzzy SETS exercises and conversations is another important consideration. If the exercises occur too early in the process of modeling a complex system, the elements of importance may not yet be identified or defined by the group; not early enough, and the opportunity to use these exercises as a consensus-building tool may be missed. Based on the results of this study, we identified fuzzy SETS as having the potential to facilitate "co-productive agility," or the "willingness and ability of diverse actors to iteratively engage in reflexive dialogues to grow shared ideas and actions that would not have been possible from the outset" (Chambers et al. 2022:102422).

Fuzzy SETS, applied alongside other system dynamics modeling as demonstrated here, is a tangible and applicable framework to address key issues that currently hinder convergence research, including lack of shared language and epistemology (Morgan et al. 2025). In the case of our Santa Fe River Watershed case CAMS study (Webster et al. 2025), we saw two ways in which our fuzzy SETS method influenced the outcome of the CAMS study. First, rather than organize the coarse-scale model in S-E-T bins (e.g., Sinha et al. 2023), these conversations steered our team to use the element types from the cross-impact matrix multiplication analysis (MICMAC) framework (see Fig. 1 caption). In addition, because we had completed the fuzzy SETS three-part exercise prior to the MICMAC survey described in Webster et al. (2025), we believe the MICMAC results were more meaningful and interpretable than if we had conducted the MICMAC survey without these prior fuzzy SETS exercises and discussions.

One challenge in current convergence research efforts is the effective integration of researchers from a social science and humanities background, which have been identified as "untapped resources" within convergence research to bring about "the convergence revolution" (NRC 2014, Peek et al. 2020). We demonstrated how fuzzy SETS provides a pathway to better integrate and explicitly acknowledge scholars from a social science or humanities background. The three-part fuzzy SETS method we presented aligns with the critical ingredients identified by Morgan et al. 2025, to take the time and effort needed to build shared understanding in interepistemic and interontological convergent teams, to acknowledge cognitive difficulties that arise in working across multiple disciplines trained in multiple methodologies, and to embrace diverse ways of knowing.

Future work

Through future work to strengthen its applicability and conceptual foundation, fuzzy SETS has potential for applications within convergent teams of researchers working on complex, wicked problems across disciplines. In the present study, we conducted the fuzzy SETS exercise with a limited group of researchers who are all working together on one research project focused on the Santa Fe River Watershed in New Mexico. Although the case study for this work focused on one specific watershed, we believe that fuzzy SETS will also be an applicable concept for groups in other watersheds, and in other non-watershed complex systems (e.g., Jasny et al. 2009, Ostrom 2009, Vespignani 2009). For future work, we have identified several key questions to pursue: How might these fuzzy SETS results and this experience look within a different complex system in a different geography or in situations in which the balance of power is typically asymmetric (e.g., with participants spanning multiple career stages, or with participants from both academic and non-academic perspectives)? Additionally, the exercise prompted researchers to don their disciplinary hat, not their interdisciplinary hat, i.e., this required researchers to categorize elements as they perceive they had been trained, not how they would actually categorize elements. One way to change this prompt could be to allow researchers to assign themselves a Likert-scale membership value within a menu of disciplines, much like they assigned a Likert-scale membership value to elements. Repeating this exercise with groups of researchers still in training, for example, within undergraduate and graduate courses, may offer more insight to the impacts of disciplinary training versus individual assessment than the present study.

The current exercise categorizes researchers into three large disciplinary categories. Future studies could also further explore these conversations within more specific disciplinary groupings, rather than three broad umbrellas (e.g., department-level groupings). In addition, future studies could apply the fuzzy SETS framing and associated activities with an academic and non-academic group (e.g., with decision makers and community members).

To support the integration of social science and humanities within convergence research, our line of inquiry provides future opportunities to examine patterns in perception-gaps (e.g. non-social experts perceiving policy innovation to be more social than others, ecological experts perceiving more themes to be interdisciplinary than others, etc.) to promote the effectivity and efficacy of interdisciplinary partnerships. Future studies could draw on quantitative fuzzy SETS literature on perception gaps (e.g., Chow and Ng 2007) and fuzzy distances (Tran and Duckstein 2002). Ultimately, such an exercise may elevate the appreciation for the team diversity and for the project complexity (Stoller 2020). Future work is also warranted to examine the role of fuzzy SETS in qualitative systems thinking and quantitative system dynamics modeling efforts, in which one element modeled within a system may be situated within multiple sectors or submodels (e.g., a dam that provides an ecological function, technological function, and societal function, or social capital, which could both enable and be enabled by technological development and/or ecological conditions).

CONCLUSION

We introduced the conceptual framing of fuzzy SETS to facilitate convergence research conducted by large, multi-, inter-, and transdisciplinary teams working on characterizing and modeling complex systems, then presented a three-part method for applying fuzzy SETS within convergent research teams. Fuzzy SETS facilitates convergence research, and any inter- or cross-disciplinary research, by providing a conceptual framework and framework of activities to build mutual understanding and clear communication between researchers from different disciplinary backgrounds, both key ingredients to successful collaborative research (Eigenbrode et al. 2007). In the proposed fuzzy SETS framework, a single system element can have varying levels of membership within multiple categories (e.g., social, ecological, or technological) within a SETS model. Fuzzy SETS, as a conceptual framework and as applied through the presented three-part activity, is proposed as one way to help teams represent diversity within groups, rather than grouping all researchers (or other groups) under one uniform umbrella, as has often been portrayed in previous research (e.g., Gray et al. 2012, Hansson and Polk 2018). Importantly, fuzzy SETS does not require that a diverse team from a wide range of disciplinary backgrounds agree on every aspect of an element. Instead, fuzzy SETS provides a framework in which different views can coexist without violating principles of others and strives to balance the challenges of honoring diversity within multidisciplinary teams while building enough consensus as a team to offer a path forward for investigating complex systems. A fuzzy SETS approach facilitates inclusivity and enriches collaborative dynamics in interdisciplinary and transdisciplinary collaborations.

Author Contributions:

YCL and AJW coordinated the development, conceptualization, design, and analysis of the study, and share co-first authorship for this article; YCL wrote the original draft of the manuscript and led the revision process. DC, MCS, and CS also contributed to conceptualizing the study. CS additionally contributed to the analysis. Following the first three authors (YCL, AJW, and CS), the remaining authors are listed alphabetically to indicate equal contribution in discussion of concepts in the original workshop (six sessions, January-February 2022) and monthly follow-up meetings through 2022. MCS is placed as the senior last author position to signify unique contributions to project oversight, mentorship, and funding acquisition. All authors also participated in revising and editing the manuscript, and all authors approved the final manuscript.

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Data Availability:

The code that supports the findings of this study is available upon request.

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APPENDIX 1: Santa Fe River Watershed Case Study: Coarse-scale element glossary

Note: See Box 1 and Webster et al. (2025) for more detail about the case study and context in which this glossary was created.

Table A.1.1 Elements considered in the case study SETS based on the Santa Fe River Watershed, with element names, abbreviated element names referenced in subsequent figures, definitions, and citation for definitions included where applicable.

Element name [abbreviated name, if different]	**Definition**
Adaptive capacity	A component of resilience that reflects the learning aspect of system behavior in response to disturbance. Systems with high adaptive capacity are more able to re-configure without significant changes in crucial functions or declines in ecosystem services (i.e., they have more resilience). Adaptive capacity in ecological systems is related to genetic diversity, biological diversity, and the heterogeneity of landscape mosaics. In social systems, the existence of institutions and networks that learn and store knowledge and experience, create flexibility in problem solving and balance power among interest groups play an important role in adaptive capacity. Definition adapted from: (Carpenter et al. 2001, Folke et al. 2002).
Agricultural water use [Agricultural water]	The total amount of water withdrawn or diverted from its source to be used for growing, harvesting, or packing of crops and rearing of animals for food and fiber. Definition adapted from: (Reig 2013, CDC 2016, Mirriam-Webster 2023a).
Biodiversity	The diversity of genes, populations, species, communities, and ecosystems across scales, including alpha, beta, and gamma diversity at different scales. Alpha diversity refers to the diversity within a particular area or ecosystem, and is often expressed by the number of species (i.e., species richness) in that ecosystem. If we examine the change in species diversity between several areas or ecosystems, we are measuring the beta diversity. Gamma diversity is a measure of the overall diversity for the different areas or ecosystems within a region. Definition adapted from: (Mace et al. 2005, Bynum 2022).
Ecosystem services	Ecosystem services are the benefits people obtain from ecosystems. These include provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services, such as nutrient cycling, that maintain the conditions for life on Earth. Definition adapted from: (Millennium ecosystem assessment 2005).
Environmental disturbance regimes (ecological, climactic, pollution-caused) not including fire [Environmental disturbances]	The type, size, frequency, severity, and timing (i.e., the regime) of events or series of events that disrupt ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment. Disturbances can be press forcings, meaning they cause cumulative disruption gradually, or pulse forcings, meaning they are relatively discrete. Definition adapted from: (Pickett and White 1985, Collins et al. 2011).
Forest management approaches and wildfire response [Forest management]	The combined scientific, technical, administrative, legal, economic, and social activities and planning processes that are applied to forest ecosystems by humans to achieve a desired set of ecosystem services. We include in this how wildfires are responded to and managed as discrete events and series of events. Definition adapted from: (FAO 2020).
Formal (legal) governance [Formal governance]	The “written” rules, regulatory processes, mechanisms, and organizations through which political actors influence actions and outcomes. Contrast to informal governance. Definition adapted from: (Chaffin et al. 2014, Steelman 2022).
Incorporation of traditional watershed knowledges into broader understanding and approaches [Traditional knowledges]	The extent to which the knowledge, histories, innovations, and practices of indigenous and local communities are incorporated into shared public understanding about a watershed, as well as systems of formal and informal governance, policy, management, and other activities in a watershed. Definition adapted from: (Traditional knowledge 2023, ANSC 2023).
Informal governance	A set of “unwritten” rules, practices, and social networks that develop and are maintained outside of formal legal rules, practices, organizations/institutions through which political actors (individuals, groups, and entities with political influence) influence actions and outcomes. Definition adapted(Adapted from the following references to make more specific to informal forms Chaffin et al. 2014, Steelman 2022).
Infrastructure	The physical systems involved in the production, storage, and/or transportation/distribution of public goods. Can include human-made and non-human made components that are interconnected. Definition adapted from: (Investopedia 2023, EPA 2023).

Land use land cover [LULC]	Structural heterogeneity of the land surface, including the physical attributes of vegetation, surfaces, and structures on the landscape, as well as attributes that reflect human decisions about how land is used. Definition adapted from: (Cadenasso et al. 2007).
Municipal water use [Municipal water]	The total amount of water withdrawn or diverted from its source to be used in the public water supply system, which may include domestic use, industrial use, and municipal landscaping, among others. Definition adapted from: (Kohli et al. 2010, Reig 2013).
Policy innovations	A new idea or method through which government improves its ability to solve problems and achieve its goals. Definition adapted from: (Hsu 2018).
Public watershed education approaches and knowledge [Public education]	Interdisciplinary place-based education both inside and outside of schools, aimed at the public broadly, that is integrated by its relevance to how a particular watershed functions, and the knowledge accumulated by the public through this process. Definition adapted from: (Stapp 2000, public education 2023).
Social capital	The benefits derived from being social, including the store of solidarity, goodwill, and trustworthiness between people and groups of people, the nature of these social connections, the norms and shared understandings that influence our action and interaction. Definition adapted from: (Claridge 2014, 2020).
Soil structure and function [Soil]	The organization of soil's abiotic and biotic components and how this determines its stability, its ability to support life, and how it exchanges nutrients, energy, and water with connected environments. Definition adapted from: (Ponge 2015).
Technical innovations	A new idea, method, or device that improves application of scientific knowledge to fulfill practical human needs. Definition adapted from: (Collins 2023, Mirriam-Webster 2023b).
Water quantity, quality, and availability [Water properties]	The extent to which water is present, available, and suitable for a particular use based on its spatial, temporal, physical, chemical, and biological characteristics. Definition adapted from: (Cordy 2001).
Watershed economics	The production, distribution, and consumption of wealth within a watershed. Definition adapted from: (Blaug 2023).
Weather and climate regimes [Weather + Climate]	The combination of air pressure, temperature, humidity, wind speed and direction, precipitation, solar radiation and other events in our atmosphere over the short and long term and how these manifest into forcings of different types, sizes, frequencies, severities, and timings. Definition adapted from: (NOAA NCEI 2018).
Wildfire regime [Wildfires]	The type, size, frequency, severity, and timing (i.e., the regime) of wildfire events. Definition adapted from: (Pickett and White 1985).

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APPENDIX 2: Fuzzy SETS survey instrument

Note: some of the description below appears in the main body of the text, but additional details are provided in this appendix for clarity and ease of reproducibility by other researchers.

The second part of the Fuzzy SETS exercise applied in this study was a survey completed individually that asked each researcher to characterize each of the system elements through the Fuzzy SETS framework. Qualtrics, an online survey platform, was used as the survey platform to collect responses from the team (Qualtrics, Provo, UT, see Acknowledgements). Before completing the membership section, each researcher is asked to define the three terms “social”, “ecological”, and “technological” according to their own discipline or personal understanding. Before starting the Fuzzy SETS categorization portion of the survey, researchers were asked to put on their "disciplinary hat" – that is, to think as they have been trained within their discipline – and assign the strength of membership of an element amongst 3 categories (social, ecological, and technological) from 0 (no membership) to 10 (full membership) (see Figure A.2.1 and Question 7 in Table A.2.1). For any given element and/or category, the researcher has the option to respond "I don't know" rather than assign a number, and every likert-scale question was accompanied by a free-response question to express any clarification or nuance. For each element, individuals were invited to share their thoughts on any of the membership levels that they indicated (Question 8, Table A.2.1). All members of the team reviewed the questions together and reviewed instructions prior to completing this part of the exercise. We then mutually agreed upon a one week timeline to complete the survey on our own time. While this could have been performed in-person and in-real-time (without the need for a survey platform), a digital platform was favored to allow for maximum flexibility and inclusion, given the realities of scheduling a group of this size (11 researchers). In addition, designing this activity as an individual, asynchronous exercise allowed individuals to think at their own pace through each question and not be influenced by potential questions or comments by others.

Table A.2.1. Self-reflexive exercise, part II: individual classification activity

Background on researcher	
Question	*Response type*
1. What is your primary discipline?	Multiple choice (select 1): Social science/humanities; physical/natural sciences; technology/engineering
2. What is your current academic department?	Free response
3. If your current academic department is not representative of your academic training, please provide more details here about your academic path.	Free response
Describing social-ecological-technological systems (SETS) Directions: First, we ask you to define these terms according to your own discipline or understanding. Next, we ask: how would you rate the strength of membership of the following elements in the following systems: social systems, ecological systems, technological systems? Please wear your "discipline hat" in answering these questions. 0 is no membership; 10 is full membership. There are no right or wrong answers, but you may use the "I don't know" option if needed.	

Question	*Response type*
4. How do you define "social"?	Free response
5. How do you define "ecological"?	Free response
6. How do you define "technological"?	Free response
** The following two questions were repeated for all elements defined in Table A.1. An example of the question on the survey is shown in Figure B.1.*	
7. * How would you rate the level of membership of [element name] in the following systems (social systems, ecological systems, and technological systems; 0 = no membership; 10 = full membership)?	Likert-type scale (0-10; I don't know)
8. * OPTIONAL: Please share your thoughts on any of the membership levels indicated in the previous question regarding [element name].	Free response

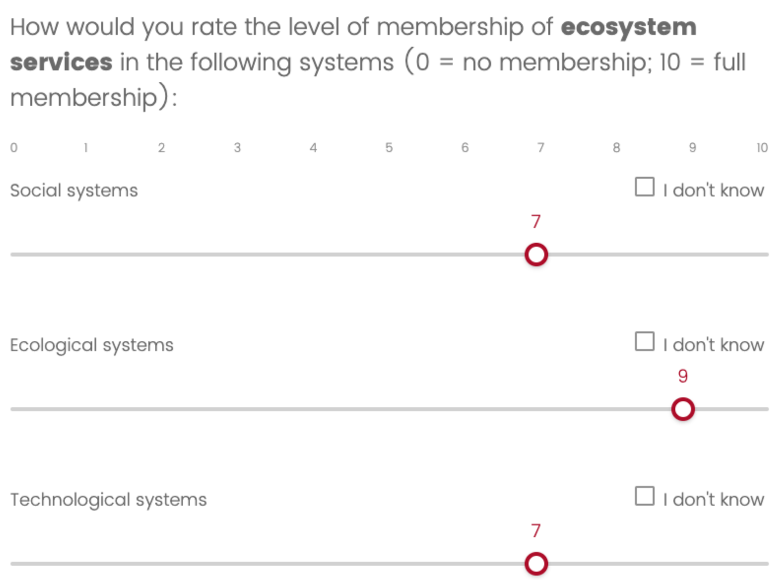

Figure A.2.1. An example of Part I of the self-reflexive exercise, Question 7* from Table B.1. The pictured response is not a real response, but provided to show how the question was asked and the mechanism for answering. A question like this was presented for each of the 20 elements in Table A.1.1.