

Operationalizing the social-ecological systems framework to assess sustainability

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Environmental governance is more effective when the scales of ecological processes are well matched with the human institutions charged with managing human–environment interactions. The social-ecological systems (SESs) framework provides guidance on how to assess the social and ecological dimensions that contribute to sustainable resource use and management, but rarely if ever has been operationalized for multiple localities in a spatially explicit, quantitative manner. Here, we use the case of small-scale fisheries in Baja California Sur, Mexico, to identify distinct SES regions and test key aspects of coupled SESs theory. Regions that exhibit greater potential for social-ecological sustainability in one dimension do not necessarily exhibit it in others, highlighting the importance of integrative, coupled system analyses when implementing spatial planning and other ecosystem-based strategies.

coupled natural and human systems | marine | governance | small-scale fisheries | conservation science

A central challenge facing humanity is how to achieve sustainable outcomes that benefit both people and nature (1). Using a social-ecological systems (SESs) approach in the generation of knowledge and the formulation of sustainable governance solutions is critical, as it explicitly recognizes the connections and feedbacks linking human and natural systems. Understanding how the potential for social-ecological sustainability varies with context is vital to solving this dilemma (2, 3). A highly visible conceptual tool, the SESs framework (4) offers the potential to address this scientific and societal challenge, but operationalization has been elusive. In this study, we demonstrate how the framework can be applied in a new way to identify opportunities and tradeoffs in managing for the sustainability of coupled SESs (5, 6).

The SES framework enables the integration of data from diverse natural and social science disciplines, and thus provides a theoretically grounded means of testing hypotheses about the dynamics and implications of social-ecological interactions (see *SI Appendix* for further discussion). At its broadest level, the SES framework describes the four essential dimensions, or first-tier variables, of a SES (Table 1, after ref. 4). Actors within and outside government operate within a Governance System characterized by formal and informal rules at one or more identifiable geographic scales. Resource Units inhabit and interact with a broader Resource System that is characterized by particular ecosystem types and biophysical processes, also at one or more geographic scales. Interactions among these four dimensions are mediated by the broader social, economic, and political settings and related ecosystems within which the SES is embedded. Together, these dynamics lead to diverse outcomes at particular

temporal and spatial scales (*SI Appendix*, Fig. S1). To operationalize the framework, we translated these four dimensions into quantitative, theoretically derived measures of factors known to contribute to sustainable resource use (see following and *SI Appendix* for a detailed description of the materials and methods).

We used the SES framework to assess the spatial variation in the potential for social-ecological sustainability of small-scale fisheries in the Mexican state of Baja California Sur (BCS). We focus on small-scale, coastal fisheries because of their importance to human communities for both income and food security (7), as well as the effects fisheries have on marine populations and ecosystem

Significance

Meeting human needs while sustaining ecosystems and the benefits they provide is a global challenge. Coastal marine systems present a particularly important case, given that >50% of the world's population lives within 100 km of the coast and fisheries are the primary source of protein for >1 billion people worldwide. Our integrative analysis here yields an understanding of the sustainability of coupled social-ecological systems that is quite distinct from that provided by either the biophysical or the social sciences alone and that illustrates the feasibility and value of operationalizing the social-ecological systems framework for comparative analyses of coupled systems, particularly in data-poor and developing nation settings.

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Table 1. SES variables analyzed for BCS's small-scale fisheries

Variable	Weight*
Dimension 1: Governance System	1.00
1. Operational and collective-choice rules	0.50
2. Territorial use privileges	0.25
3. Fishing licenses	0.25
Dimension 2: Actors	1.00
4. Diversity of relevant actors	0.20
5. Number of relevant actors	0.20
6. Migration	0.20
7. Isolation	0.20
8. Livelihood diversity potential	0.20
Dimension 3: Resource Units	1.00
9. Diversity of targeted taxa	0.50
10. Per capita revenue	0.50
Dimension 4: Resource System	1.00
11. System productivity	0.33
12. System size	0.33
13. System predictability	0.33

*Weight refers to the weight given to each lower-tier variable (numbered 1–13), when used to calculate the four first-tier variables (i.e., Dimensions). See *Materials and Methods* and *SI Appendix, section 2* for details.

health (8). We define the potential for social-ecological sustainability as the likelihood that human and nonhuman components of the focal coupled SES will be maintained so as to meet the needs of both people and nature, now and in the future (3, 4).

Previous work has highlighted that the matching of ecological and institutional scales increases the likelihood for sustainable governance of fisheries and other common pool resources (e.g., refs. 6, 9, and 10). However, contemporary environmental governance regimes often neglect the array of social, institutional, and ecological factors known to be vital to develop potential for social-ecological sustainability (e.g., refs. 4 and 11–13). We hypothesized that those regions of BCS with greater potential for social-ecological sustainability in the ecological dimensions (i.e., fish populations and the marine ecosystems they are part of) would exhibit greater potential in the social dimensions (i.e., fishers and the institutions that govern fishers' interactions with BCS' marine ecosystems) (*SI Appendix, Fig. S1*). We also hypothesized that measures of the two social system dimensions (Actors and Governance System) would be positively correlated, as would the measures of the two ecosystem dimensions (Resource System and Resource Units), given the linkages within the social and ecological domains (*SI Appendix, Fig. S1*). Finally, we predicted that we would observe substantial spatial variation in the potential for social-ecological sustainability.

Results

To test these three hypotheses, we first mapped regions of major small-scale fishing activity in BCS. These regions, hereafter referred to as SES regions (Fig. 1), were derived using data from the peer-reviewed literature, government environmental and economic data, and expert knowledge from fishers, resource management and conservation practitioners, and researchers (see *SI Appendix* for details). This map was essential for the translation of the SES framework and hypothesis tests we report here. If, instead, we had relied on a political map, delineating the five municipalities (*SI Appendix, Fig. S2*), we would have been unable to incorporate well-known differences in biogeography and human population density between the Gulf and Pacific coasts of BCS. Relatedly, a map based primarily on environmental factors (e.g., refs. 14 and 15) would not have captured documented variation in adaptive capacity, local institutions, and market dynamics related to small-scale fisheries (16–18).

To operationalize the SES framework for our focal system, we identified 13 variables that have been linked to the likelihood of the emergence of locally appropriate governance of SESs, and small-scale fisheries SESs in particular (19). These 13 variables were nested underneath the four dimensions introduced earlier (Table 1). We then identified indicators for each of the 13 variables and quantified them on the basis of primary data (Table 2). Once we calculated indicators for all 13 variables on a common scale and then created composite, quantitative measures of each of the four SES dimensions (i.e., first-tier variables), we were able to test our hypotheses of social-ecological alignment, within-domain correlation, and spatial variation in the potential for social-ecological sustainability. Fig. 2 provides a visualization of our methods.

Contrary to the first hypothesis, we found few consistent positive relationships between the social and ecological dimensions related to the potential for sustainable resource use (Fig. 3 and *SI Appendix, Results*). Among the a priori tests we conducted regarding the first-tier SES variables, only one pair exhibited the predicted relationship. Regions characterized by high Governance System scores also had high Resource Units scores (Fig. 3; linear regression: $R^2 = 0.33$; $F_{1, 10} = 4.86$; $P = 0.05$). This association was particularly evident for regions with the highest and lowest sets of scores: Pacifico Norte and Todos Santos and Cabo San Lucas, Gulf of Ulloa and East Cape, respectively (Fig. 4).

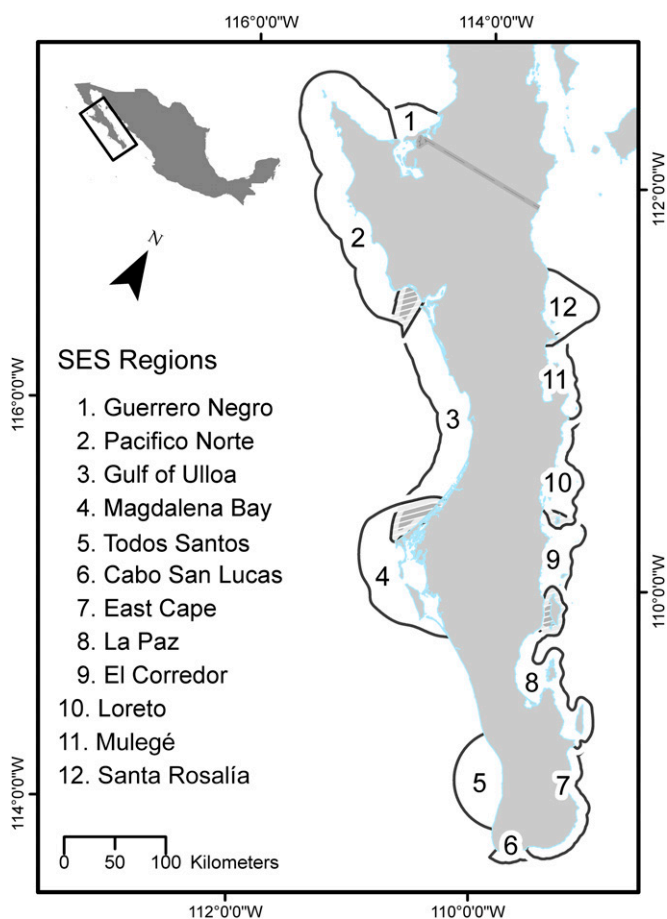


Fig. 1. The 12 SES regions identified for BCS, Mexico, based on the extent of small-scale fishing activity by members of fishing communities throughout the state. The hatched areas indicate overlaps between adjacent regions; that is, where fishers from different regions report using the same areas. Fishing occurs on the Pacific coast between regions 4 and 5, but existing information did not yield a distinct SES region.

Table 2. Representative data used to calculate the scores for the four first-tier SES variables

SES region	Index, local rules	Total number of fishers	Taxa reported	Per capita revenue, \$USD	Mean chlorophyll <i>a</i> (chl <i>a</i>), $\mu\text{g}\cdot\text{m}^{-3}$	CV (coefficient of variation), mean chl <i>a</i>
1. Guerrero Negro	0.42	293	39	12,434	2.73	20.20
2. Pacífico Norte	1.00	1,083	73	15,123	1.76	57.86
3. Gulf of Ulloa	0.25	614	85	14,467	2.64	68.76
4. Magdalena Bay	0.25	1,283	90	15,060	2.19	50.20
5. Todos Santos	1.00	77	59	22,243	1.13	109.12
6. Cabo San Lucas	0.25	81	9	2,337	0.84	76.04
7. East Cape	0.25	247	36	2,641	0.88	65.28
8. La Paz	0.25	974	55	986	1.22	58.51
9. El Corredor	0.25	102	52	8,320	1.15	59.16
10. Loreto	0.58	152	44	5,220	1.43	57.25
11. Mulegé	0.58	126	54	6,750	2.31	46.51
12. Santa Rosalía	0.25	523	67	9,803	1.50	45.54

The full dataset can be found in [SI Appendix, Table S2](#).

Neither the two first-tier social system variables (Actors and Governance System) nor the two first-tier ecosystem variables (Resource Units and Resource System) were associated, contrary to our second hypothesis (Fig. 3; $P > 0.10$). However, these analyses revealed the dimensions within which the potential for sustainable resource use and governance is particularly high or low, which could inform future capacity-building efforts and other policy and management interventions. For example, although El Corredor's Governance System score was the lowest of the 12 regions, its Actors score was almost as high as that of Pacífico Norte, indicating that El Corredor already exhibits substantial potential for sustainable resource use in the latter dimension (Fig. 4 and [SI Appendix, Table S4](#)).

Finally, the potential for social-ecological sustainability varied substantially among the SES regions, as predicted (Fig. 4). As reported earlier, regions that scored high in one dimension (i.e., one first-tier variable) did not necessarily score high in all four dimensions. Magdalena Bay and Gulf of Ulloa, for example, had Resource Units scores close to 1 ([SI Appendix, Table S4](#)), yet the Actors scores for these two regions were both less than the median. Cabo San Lucas, East Cape, La Paz, and Loreto had some of the lowest scores overall (linear contrast of scores by region: $F_{1, 36} = 13.08$; $P = 0.001$). Principal components analysis provided another means of visualizing spatial variation among the regions, suggesting there are multiple paths to achieving sustainability ([SI Appendix, Fig. S3](#)). The results of the first-tier variable analyses were also reflected in the primary data (Table 2 and [SI Appendix, Table S2](#)). Together, these analyses illustrate substantial spatial heterogeneity in the potential for sustainable resource use related to small-scale fisheries in BCS and also elucidate how this variation is created by a combination of social and ecological factors ([SI Appendix, Figs. S4–S8](#)).

Discussion

Our approach illustrates how diverse qualitative and quantitative datasets can be integrated in a robust and spatially explicit manner to describe multiple SESs and to test related theory. Analyses of the theoretically grounded measures we created (Table 1 and [SI Appendix, Tables S2–S4](#)) revealed that regions that are strong in one dimension are not necessarily strong in the other three (Figs. 3 and 4 and [SI Appendix, Table S3](#)). Moreover, variation in the potential for social-ecological sustainability exists at a finer spatial scale than that at which the state currently regulates small-scale fisheries (as described in detail in the [SI Appendix](#)).

Our translation of the SES framework also highlights how assessments based on solely biophysical or social data may lead

to quite divergent conclusions. Consider, for example, Magdalena Bay, where fishers report the most taxon-rich catches of the 12 SES regions. Previous theory and empirical work suggest that such ecological diversity should buffer the coupled SES from disturbances and confer resilience in the face of environmental and institutional changes (20). However, although Magdalena Bay had a very high Resource Units score, its Actors score was among the lowest. So, depending on which type of data one musters regarding the potential for sustainable fisheries, Magdalena Bay could be scored as either well-endowed or quite weak. Perhaps more important, this result suggests that in the Actors dimension, there is opportunity to build management capacity (e.g., by increasing the ratio of permitted to illegal fishers), whereas in the Resource Units dimension, it may be more important to maintain existing management capacity (e.g., by creating institutions to help ensure continued diversity of targeted taxa). These scores are consistent with our personal experiences in this particular region, where the sheer number of fishers, including many unpermitted fishers, and the diversity of gear types and interests they represent contribute to significant social conflict.

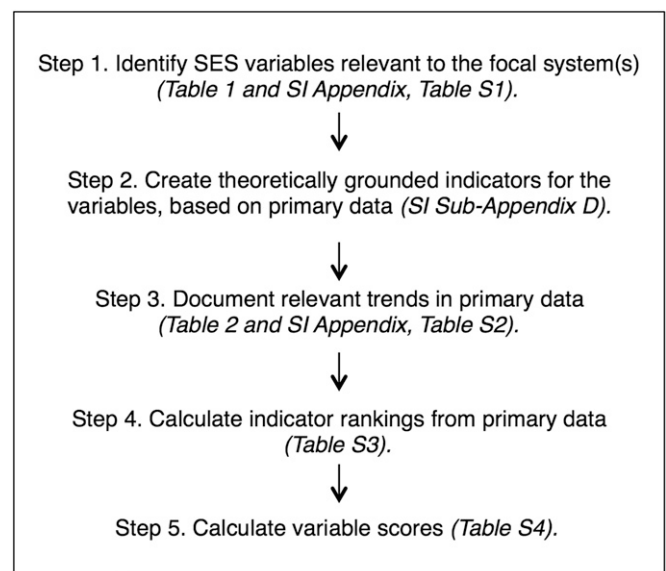


Fig. 2. Steps to translate the SES framework into quantitative measures of the potential for social-ecological sustainability, with references to the relevant [SI Appendix](#) sections.

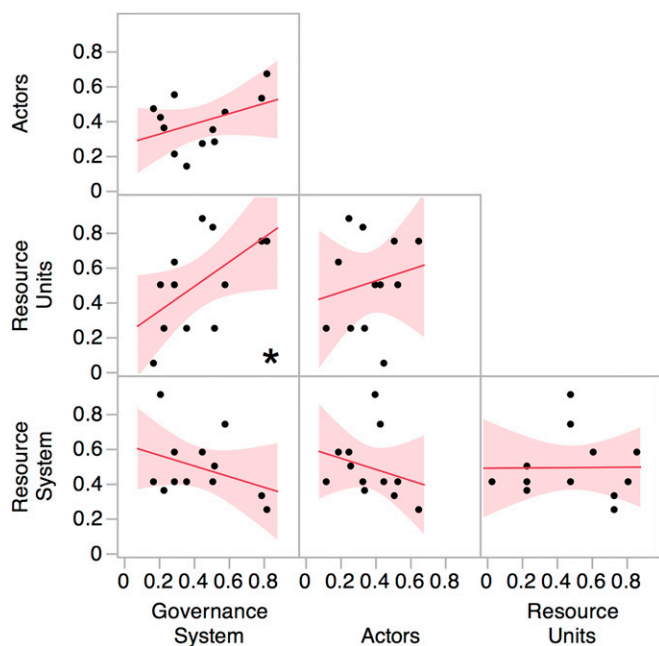


Fig. 3. Scatterplot of the relationships among all four SES dimensions or first-tier variables demonstrates the heterogeneity, both among the four dimensions and among regions, in the potential for sustainable resource use and management in BCS, Mexico. Values range from 0 to 1, where a larger value is associated with a greater probability that fisheries will be sustainably managed. Details regarding the quantification of these dimensions and underlying data and theory can be found in the *SI Appendix, Sub-Appendix D*. The solid lines are fit with simple linear regression models, and the shading refers to the 95% confidence intervals. Only one model (marked with an asterisk) was significant at $\alpha = 0.05$.

These results demonstrate how integrative, interdisciplinary research that includes both qualitative and quantitative data may be synthesized to yield a richer understanding of coupled SESs in particular places. Many of these data have never before been mapped at this scale, and yet such fine-scale information could help inform implementation of ecosystem-based fisheries management, marine spatial planning, and related strategies. The variation among the SES regions suggests that certain marine management strategies, implemented at particular geographic scales, are likely to be more effective in some places than others (see also refs. 21 and 22).

Mapping is necessarily a political project in which local actors must be involved to negotiate boundaries in ways that are more likely to lead to just outcomes (23, 24). Our purpose here is not to portray the SES regions as definitive boundaries but, rather, to encourage finer-scale, spatially explicit governance of SESs, in which local stakeholders participate in the necessary refinement of social-ecological management boundaries. Stakeholder engagement will require and also provide an impetus to create finer-resolution spatial data at the level of individual fishing communities. To our knowledge, these are not yet available for most of BCS and other coastal marine SESs around the world. To extend our approach and to evaluate spatial heterogeneity in the actual interactions and outcomes associated with small-scale fisheries will require substantially more and different types of data than those currently available.

The diversity of species and fishing practices that are inherently part of small-scale fisheries like BCS' present other challenges for coupled systems analyses, and for the SES framework specifically. By design, the framework focuses on interactions between resource users and other actors regarding a specific resource in the context of a particular SES. However, small-scale fishers target tens, if not

hundreds, of species, which vary in their life histories, economic value, and many other important characteristics. We managed this complexity by scaling up our analysis to the level of major fishing areas, which represented fishers' use of ocean space to catch many species over the entire year (Fig. 1). Nonetheless, this level of analysis obscures some valuable information.

Similarly, although we can think of biogeographic, oceanographic, and human history as exogenous drivers of the dynamics of a given SES region, on long time scales, they are not static. Global climate change continues to alter the biophysical template on which social-ecological interactions play out; for example, by changing water and air temperatures and the frequency and magnitude of precipitation and coastal storms. Sociopolitical dynamics enter the SES framework both as context and in relationships between attributes internal to the coupled system (25). Evolving sociopolitical dynamics from local to national scales and their interactions with narco-trafficking and other multinational influences shape the opportunities and constraints facing BCS' small-scale fishers and their decisions about how, where, and when to fish (as in ref. 26).

Our analyses inform four types of management strategies, focused on each of the four dimensions (or first-tier SES variables). Interventions focused on improving existing institutional arrangements are most likely to strengthen the Governance System dimension, whereas those focused on improving relationships among stakeholders will aid in building capacity in the Actors dimension. Similarly, we anticipate that strategies focused on maintaining or improving ecosystem health would benefit the Resource System dimension, and that interventions focused on improving the status of populations of the target species would build capacity in the Resource Units dimension. Such tailored strategies will likely reduce the costs associated with blueprint, or one-size-fits-all, types of policies. Given the physical isolation and consequent high reliance on marine resources in the Pacifico Norte and El Corredor regions, for example, especially when contrasted with the highly populated southern regions, a blueprint approach to fisheries management and MPA implementation will not serve either the human communities or the marine ecosystems of BCS well. Instead, we advocate for more strategic approaches, targeted to the needs and strengths of specific regions. However, it also is important to acknowledge that governance approaches tailored to address problems in one dimension or region could trigger unintended consequences in other dimensions or regions if issues are not addressed holistically. Applying integrative, place-based understanding of SESs in this and other geographies will enable sustainability science to more fully inform sustainability practice.

Materials and Methods

SES Mapping. To map the SES regions, we began by listing all the small-scale fishing communities along the coast of BCS, with reference to ref. 27. We then identified distinct clusters among them based on four primary factors: biophysical context, including coastal topography, habitats, and species distributions; historical and contemporary coastal land and marine resource use; municipal and state political boundaries; and the concentrations and movement of fishers and fisheries products. Further detail on these factors and the current fisheries management regime can be found in the *SI Appendix, Sub-Appendix A*.

Based on these first two steps, we drew an initial map of major fishing areas of BCS. This initial map informed a series of unstructured interviews with key informants about the scale and nature of small-scale fisheries activities throughout BCS. Fourth, following refinement of the maps based on the results of the interviews, we created a survey instrument to elicit standardized area-specific expert knowledge of the human and environmental dimensions of BCS' small-scale fisheries from fisheries managers and conservation and community development practitioners. The survey was distributed to 15 individuals and is included as *SI Appendix, Sub-Appendix B*. After analysis of the survey results, the SES regions were amended as needed. Further details on the mapping protocol can be found in *SI Appendix, Materials and Methods*, along with detailed descriptions of

