Operatorulizing the social-ecological systems framework to assess sustainability

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Abstract

Understanding 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, as well as the effects fisheries have on marine populations and ecosystem services. Using a social-ecological systems (SES) approach in the generation of knowledge and the formulation of sustainable management 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. A highly visible central challenge facing humanity is how to achieve sustainable outcomes that benefit both people and nature. Operationalizing the SES framework to translate 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).

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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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: Pacífico Norte and Todos Santos and Cabo San Lucas, Gulf of Ulloa and East Cape, respectively (Fig. 4).

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

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

*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.
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 these four regions vs. the other eight, following ANOVA 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.](image-url)
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 apply 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 distributions of other geographies 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 Pacífico Norte and El Corredor 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.

![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 $a = 0.05$.](image-url)
each region (SI Appendix, Sub-Appendix C). The SES regions map and all other maps were produced using ESRI ArcGIS 10.1.

Operationalizing the Framework. Once we had an appropriate map with which to test our hypotheses, we translated the SES framework from a conceptual model into a quantifiable set of indicators, linked with each of the four SES dimensions or first-tier variables. The 13 lower-tier variable selection process was driven by our knowledge of the BCS SESs, review of the scholarly literature, and theoretical underpinnings of our work, including the governance of common-pool resources and the relationships between biodiversity and ecosystem function. Fig. 2 provides a step-by-step visualization of the full methods.

Variable Selection and Ranking of the Indicators. A varying number of second, third, and fourth-tier variables are nested under each of the four dimensions (Governance System, Actors, Resource System, and Resource Units); in total, there are 13 second-, third-, and fourth-tier variables (Table 1 and SI Appendix, Table S1, after refs. 4 and 19). Importantly, all 13 variables, regardless of whether the primary data used to develop the indicator were qualitative or quantitative, were normalized to a scale of 0–1, so they could be combined and compared. For those variables for which the primary data were continuous, such as total fisheries biomass, the values for each SES region were calculated on the basis of the quantile distribution of the original data. For those variables for which the primary data were qualitative (e.g., presence/absence), they were translated into categorical 0/1 variables. These data and the resulting rankings are presented in SI Appendix, Tables S2–S4.

SI Appendix, Sub-Appendix D includes the description of all 13 SES variables and the related indicators. The description includes each variable’s name, position in the original SES framework (4), definition, theoretical importance, a brief description of the indicator or indicators associated with the variable, and the ranking system for each indicator. Where appropriate, we include the quantile distribution of the original data. For each variable, we identified one or more indicators that enabled either qualitative or quantitative comparison among the 12 SES regions. Together, these complementary indicators captured multiple dimensions of a variable. We developed the ranking system from relevant theory regarding how each variable has been associated with a SES’s potential for sustainable resource governance.

Variable Weighting. Each of the four dimensions, Governance System, Actors, Resource Units, and Resource System, has a cumulative weight score of one (Table 1). The relative contribution of each of the lower-tier variables to this weight depends on the total number of such variables analyzed under a particular dimension, or first-tier variable. For example, the dimension Actors is composed of five lower-tier variables, each of which is weighted 0.20 for an overall score of 1.00 (Table 1 and SI Appendix, Table S1 and SI Appendix, Sub-Appendix D). For the variables that have more than one indicator (SI Appendix, Table S2 and SI Appendix, Sub-Appendix D), scores were averaged before being weighted.

Data and Analyses. The data can be found in SI Appendix, Tables S2–S4. All statistical tests were performed using JMP 11 (SAS Institute) or SPSS 22.0 (SPSS Statistics Inc.). We used standard statistical approaches (i.e., linear regression, analysis of variance, and principal component analysis models) to explore the primary data used to develop the indicators for the SES variables and test a priori hypotheses regarding the first-tier SES variables. Before analysis, the primary data and the calculated variables were plotted to investigate their fit to statistical assumptions; for example, normality. When necessary, data were transformed. The details of these models are described in SI Appendix, Results.

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