



Looking back to shape the future: Trajectories and resilience of social–ecological systems in the Global South

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Abstract In complex Social-Ecological Systems (SES), the interplay between ecological and social components shapes trajectories that impact human well-being and ecosystem services. While SES dynamics have been studied in static conditions, there has been less attention to how said systems respond to shocks and stressors over time and space. This special issue presents a collection of articles that use diverse methodologies—ranging from system dynamics modeling to participatory approaches—to analyze past SES changes and discuss future scenarios. Case studies from regions including Brazil, Colombia, Mexico, Honduras, Chile, Ethiopia and Mongolia illustrate key variables influencing social–ecological transitions and provide insights into potential policy strategies to support sustainable SES. The studies underscore the need for multi-scalar approaches to SES research that explicitly theorize and empirically assess trajectories across space and time.

Keywords Models · Multi-scalar · Scenarios · Social–ecological systems · Systems dynamics · Trajectories

INTRODUCTION

In complex Social-Ecological Systems (SES) ecosystems interact with social components in time and space, resulting in outcomes that express an enhancement or degradation of well-being and ecosystem services (Leslie et al. 2015). The longitudinal study and aggregation of these outcomes results in a trajectory. To satisfy the needs of more than 8 billion people while ensuring a viable biosphere, we need to understand the trajectory of SES in the light of socio-economic and ecological trends and shocks (IPCC 2022). This

should provide insights on how to enhance the sustainability of such systems now and in the future. The SES literature finds multiple frameworks and methods for assessing changes in these systems over time and space. The ‘original’ descriptive SES framework (Berkas and Folke 1998), and the multi-tiered SES frameworks by Anderies et al. (2004) and Ostrom (2009) are one set of commonly applied approaches (see Colding and Barthel 2019). However, in their review of 5908 cases of SES research, de Vos et al. (2019) identify over 300 different methods used to analyze SES but also note that only about 15% of these studies rely on explicit analytical frameworks.

Furthermore, most SES research has provided assessments under static conditions, or it has downplayed the importance of past and present trajectories. For example, Ndong et al. (2020) show that a large majority (74%) of peer-reviewed articles-retrieved from the Web of Science—which examine the provision of ecosystem services in explicit SES between 1998 and 2017 provided an empirical snapshot and did not adopt a longitudinal perspective. Partelow’s (2018) review of SES analytical frameworks discusses commonalities across framework and case studies, in order to foster cross-case comparison and derive generalizations. However, the authors overlook the importance of integrating socio-ecological changes over time. In contrast, Li et al. (2020) emphasize the importance of understanding the dynamic nature of dominant feedback loops in SES yet do not explore in detail how to operationalize such analytical approach. Xu et al. (2024) focus on SES frameworks used to assess ecological and social vulnerability and propose to use modeling to understand changes in time and space. This allows to understand SES dynamics which helps to identify different drivers of change and their effects on the systems changing feedback loops and cascade effects.

Indeed, SES trajectories are the expression of causal mechanisms of change viewed as a sequence of states (after a regime shift) or as a stability state of a specific SES in time. A state being here defined as the maintenance across time of the value of a set of key SES variables. A regime shift would occur when those key SES variables cross a certain threshold to define a new state. While some frameworks have offered a historical approach to understand changes in time, such as the adaptive cycle or the social–ecological trap analysis (Enfors 2013; Nayak and Armitage 2018), they are very limited in scope. Therefore, we need to better apprehend the diversity of frameworks and methods that scholars are using to understand historical changes of dynamic systems (Schlüter et al. 2014; Elleaume et al. 2022). Evidence from such research should help anticipating possible future traps and undesired SES pathways, in order to support policies for a more social–ecologically sustainable future (Poli 2017).

The present special issue (SI) brings together a collection of articles that examine the ecological and social dynamics of several SES from a historical perspective, including case studies from Brazil, Colombia, Mexico, Honduras, Chile, Ethiopia and Mongolia. By analyzing past trajectories and using these to reflect on the possible futures awaiting the biosphere as a global social–ecological system, the contributions identify key variables of social–ecological change and how such variables moved—or not—the system closer to sustainable thresholds, as an adaptive learning process (Shackleton et al. 2018). For the purpose of the SI we define key variables as those that allow to describe the state and change of a particular SES process given three properties: (i) their significance to express the main issues of the research question at stake; (ii) their sensitiveness with regard to the changes in the process to be measured and; (iii) its measurability, in terms of cost and accuracy (Ezzine-de-Blas 2022). Key variables are therefore context specific: specific to the context of the research questions, the epistemology of the research group, the availability of data and the type of SES studied. The articles pay specific attention to variable interactions, as well as socio-ecological trade-offs, with an emphasis on questions of governance and adaptability, taking into account current and more desirable social–ecological trajectories. In what follows, we present the contributions in more detail and, subsequently, we suggest future research avenues.

Article contributions

Seven contributions use modeling methodologies to understand SES trajectories. These studies illustrate how different quantitative, qualitative and geospatial data can be gathered and analyzed to understand historic changes

and predict future scenarios under different institutional, social, economic and ecological conditions. One way to describe the causal mechanisms in SES is using system dynamics: Berrio-Giraldo et al. (2024), proposes a systemic modeling of the Rio Grande basin in central Colombia, to explore how different climatic and policy scenarios would affect water regulation services and farmer's income when moving into different futures. The authors use a set of land use, biophysical, socio-cultural, economic and institutional variables to model how different policy intervention scenarios influence the social–ecological sustainability of the river basin. Their results point to the importance of considering trade-offs between economic and ecological variables when modeling different policy scenarios for territorial governance, in order to avoid unintended consequences that could negatively affect the sustainability of the system.

Similarly, Martins et al. (2024) implements a dynamic system model of the water–agriculture–energy nexus in one of the major tributaries of the São Francisco basin in Southern Brazil. Their results show that rising costs and decreasing profits due to irrigation water shortages might be a brake for the expansion of irrigated land. Such irrigation shortages would also reflect a decrease in downstream flow and baseflow; while, energy demand is set to increase due to agricultural land expansion. Their work allows to anticipate what investments would be needed to avoid conflicting future trade-offs.

The works by Ramírez-León et al. (2023) and Merlo-Galeazzi et al. (2024) illustrate how Holling's (2001) adaptive cycle framework can inform the modeling of natural, social and political factors in SES. Merlo-Galeazzi et al. (2024) analyze the trajectory of the Copalita-Huatulco watershed in Oaxaca with a special emphasis on hydrological services. The authors conceptualize the trajectory of hydrological ecosystem services (i.e., water quality and quantity) by integrating the SES and adaptive cycle frameworks and using a set of semi-structured interview to document key variables driving the historical changes in the watershed. They find several changes in regional hydrodynamics due to cumulative natural shocks and social stressors, with a growth phase dominated by stressors, a collapse phase explained by the shocks occurred then, and a conservation phase driven by strong human agency. Their work advances the operationalization and measurement of the phases of the adaptive cycle and shows how drivers of change have historically affected ecosystem services, thus creating a cascade effect.

Ramírez-León et al. (2023) also apply the adaptive cycle framework to explore the historical changes of a coffee agri-food system in Oaxaca, Mexico, over a 40-year period, from 1980 to 2020. Using qualitative data and semi-structured interviews, the authors propose a method to

assess the severity and spatial scale of drivers and shocks and the capacity of the system to respond through the capacity of the system to transform. They find that the system passed through three out of the four phases of the adaptive cycle: first, the system passed from crisis to rearrangement (1980–2000), second, a period of reconfiguration and innovation (2000–2010), and a third phase that focused on reorganization and new arrangements. Although several biophysical and social stressors have affected the agri-food system over the last decades, local actors have been able to design new commercial and institutional adaptive strategies to overcome them. The result of this has been the stability of the coffee producer system, but driven by the emergence of new markets that helped to diversify income sources.

Pedraza-Gama et al. (2024) propose a spatial assessment of social–ecological systems’ vulnerability using the Ecosystem Services Assessment framework and the Social–ecological Vulnerability Mapping (ECOSER) tool. Looking at four micro-watersheds of the Ajusco mountain range, south of Mexico City, the authors compare how hydrological ecosystem services and social–ecological vulnerability would correlate in the future depending on specific climate change and conservation policies. The research shows an increase in vulnerability due to persistent deforestation, urbanization and water extraction, which correlate with a decrease in the density of hydrological ecosystem services. From a different methodological perspective but with the same regional focus, Galeana-Pizaña et al. (2024) analyze land use change drivers through neural networks and Markov chains to develop land use scenarios for two different futures: a business as usual versus a second one dominated by forest conservation policies. The results show the critical role that sustained conservation policies through protected areas and economic incentives play in the reduction of deforestation and the expansion of urban areas. However, even under strong conservation policies, mountain forests are expected to be lost for urban settlements, thus demonstrating the negative impact of incessant urbanization on the extent and quality of natural ecosystem surrounding the metropolis of the Global South.

Some contributions to the SI incorporate participatory methods that facilitate the inclusion of non-scientists and non-experts into SES modeling, thus providing a richer picture on the mental models of resource users and on the future trajectories of SES. Brück et al. (2024) propose a six-step approach for scenario analysis to address equity-related effects of land use change in decision-making. The six-steps consists of: (i) setting system boundaries and units of analysis for spatial (dis-)aggregation; (ii) developing narrative scenarios; (iii) translating scenarios into spatially explicit land use and land use change maps; (iv) analyzing biophysical ecosystem services changes and (v) socio-economic changes;

and (vi) communicating results to decision-makers. By exploring different mental models through the narrative scenarios, the authors also identify different beneficiary groups and value types in a spatially explicit way, departing from archetypes of scenarios based on main crops driving ecosystem change (e.g., woody vegetation vs khat-cropland).

In the collection, SES are also explored using mixed-methods approaches. Three contributions combine both biophysical and socio-economic and governance data to describe social–ecological historical trajectories. First, Peter et al. (2024) explore how urbanization pressures affect the intergenerational transfer of traditional ecological knowledge (TEK) among Mongolian pastoralists, using household surveys and qualitative interviews. TEK allows Mongolian herders deal with extreme events, assess and find quality pasture and manage and heal livestock. The authors find that households living under conditions of greater urbanization transformation—a proxy for competition for good pastureland—apply TEK more often than households under lower pressure do.

Second, Rivera et al. (2024) explore the historical evolution of community-based natural resource management (CBNRM) in the Bay Islands National Marine Park, Honduras, looking at the interaction between cooperation, funding, and communication and their role in supporting successful conservation outcomes. Using Gruber’s (2010) principles for community-based management, and drawing on focus group discussions, semi-structured interviews and questionnaire data, the authors show that key CBNRM principles—including an enabling environment, conflict resolution mechanisms, patrol effectiveness, public trust, and a monitoring system—have fostered a transition toward successful conservation outcomes.

Finally, Ibarra et al. (2024) assess people–tree relationships from the angle of the social–ecological memory that emerges from the relationship between communities and specific trees, in the region of La Araucanía, southern Chile. To assess such relationship in a chronological way, the authors integrate dendrochronology (analysis of tree-rings of 35 memorial trees; 17 species) with participant observation and semi-structured interviews. Their findings show that assemblages of people–tree relationships reflect marked historical changes in the territory, associated with the historical clearing of forests, which are imprinted in both tree growth rings and in the social meanings and practices associated with memorial trees.

Contributions to the state of the art and future research areas

This collection of articles sheds light on the broad methodological choices that can be adopted for the temporal and spatial analysis of SES. We can distinguish between modeling versus mixed-methods, and, within each

Table 1 Synthesis of methods, data, key variables, stressors and shocks found in the articles of the special issue

Authors	Methods	Key variables	Stressors/shocks	Data used
Alves-Martins et al. (Brazil)	Dynamic system modeling	Irrigated land Water demand for irrigation Downstream flow Baseflow	Increase water demand Rainfall decrease	National statistics, hydrological and spatial data (MapBiomass, National Water Agency, Groundwater Monitoring Network, population data, electric energy consumption) Eta-CanESM2 climate model
Berrio et al. (Colombia)	Dynamic system modeling	Erosion control Water quality Forest land Pastureland Institutional capacity Forest conservation motivations	Climate change Market prices Conservation incentives	Dynamic model of the watershed parametrized with previous research Parametrization of water quality through the index of pollution by suspended solids (IPSS)
Brück et al. (Ethiopia)	Participatory narrative scenarios InVEST Spatial regressions Surveys for ES values Stakeholder interviews	Land uses for provisioning ES per capita (cattle, firewood, honey etc.) ES specialization Values Stakeholder presence	Increased demand for export crops (coffee) and intensification	Qualitative land use change rules and scenarios obtained from several workshops with stakeholders Land use land cover map from satellite imagery
Galeano et al. (Mexico)	Spatial analysis of land use changes Neural networks	Forest and urban areas Conservation policies implementation	Urbanization Forest conservation institutions	Land use and cover change maps from 1999 to 2019 Interdisciplinary workshop to identify drivers of change Spatial distribution of conservation policies
Ibarra et al. (Chile)	Dendrochronology Ethnographic interviews	Trees' dendrochronology Deforestation Social values	Deforestation	Tree-ring analysis of 35 memorial trees Participant observation complemented with semi-structured interviews with 14 interviewees
Merlo et al. (Mexico)	Adaptive cycle documented through interviews	Hydrological ecosystem services	Urbanization Climate change	Qualitative interviews with 27 stakeholders Reports written by local experts and not available online
Peter et al. (Mongolia)	TEK as an adaptation strategy	Traditional Ecological Knowledge (TEK) Livestock Pastures quality	Urbanization	Quantitative survey of 253 households Qualitative face-to-face interviews with 301 households
Pedraza-Gama et al. (Mexico)	Collaborative Protocol for Ecosystem Services Assessment and Social–ecological Vulnerability Mapping (ECOSER) Spatial modeling	Hydrological ecosystem services Socio-ecological vulnerability	Urbanization Climate change	Historical analysis (1999–20,219) of land use changes using satellite imagery Raster layer of ecosystem functions (storage of organic carbon in biomass; retention of excess Precipitation by vegetative cover; protection of aquifers by vegetative cover) using secondary sources Climatological model BCC-CSM2-MR Structured online survey of 19 researchers and decision-makers

Table 1 continued

Authors	Methods	Key variables	Stressors/shocks	Data used
Ramírez-León et al. (Mexico)	Adaptive cycle documented through interviews	Coffee production Economic diversification	Weakening public institutions Climate change (decreased rainfall and increased temperature)	Qualitative interviews with 30 stakeholders (producer organizations, entrepreneurs, NGOs, government delegates, scientists and coffee farmers)
Rivera et al. (Honduras)	Evolution of CBNRM based on Gruber's 12 key principles	Cooperation Funding Communication Monitoring	Tourism Climate change (sea water temperature increase)	Literature review Two focus group discussions Close-ended questionnaire to 35 stakeholders Interviews to 12 experts and professionals

of them, a wide range of choices. For example, in the case of modeling, we can differentiate dynamic system modeling, which provides a clear taxonomy and modeling steps. In contrast, the adaptive cycle, could be defined more as an analytical framework or conceptual model—one in which general assumptions are used as departing research guides, but that do not imply a rigid modeling language. One attractive feature of models, particularly when backed up by solid analytical frameworks, is the possibility to modify them to create scenarios to represent possible futures: Dynamic system models, the ECOSER framework and scenarios based on narratives, did produce such scenarios in some of the articles introduced (see Berrio-Giraldo et al. 2024, Brück et al. 2024 and Pedraza-Gama et al. 2024 in this issue); while, the research work using the adaptive cycle to describe past changes did not. This could be an interesting feature in future research using the adaptive cycle framework: use the description of past phases to define causal mechanisms that would allow project them into the future. Besides, modeling systems departing from theory and past empirical evidence to propose a conceptual model might miss to identify surprise interactions between key variables that have shaped SES outcomes in the past but for which empirical evidence still does not exist. The articles that chose a mixed-methods approach to describe historical trajectories had the contrarian weakness: they lacked a conceptual model representing the processes and interactions in which key variables were involved in the past. Without such a conceptual model, to reflect about possible futures is a difficult task.

The final choice of the conceptual framework and modeling approach chosen for the study of SES, will ultimately depend on the research questions, the socio-ecological outcomes of concern, and the availability of data. Moreover, the complexity that usually characterizes SES (Ostrom 2009) compels the researcher to discriminate between the specific social–ecological interactions to be

assessed and what are the best methods that fit such purpose. Like the review findings by Colding and Barthel (2019), the articles in this SI have not used the SES key variables defined by Ostrom and colleagues (Anderies et al. 2004; Ostrom 2009; Leslie et al. 2015). Rather, they have drawn broadly from the original analytical framework proposed by Berkes and Folke (1998) to consider how various social and environmental conditions, and relevant key variables, influence SES dynamics (Table 1).

All the methodological choices to assess changes in SES over time require choosing a specific epistemology of causality, and the latter merits reflection in order to understand the benefits and limitations of specific methods and related variables. For example, theoretical economists will choose to formalize modeling through mathematical functions (Liski and Salanié 2023); while, econometricians will opt for different regression models and experimental settings (Ferraro et al. 2018). In both cases, the considerations of endogeneity and multi-collinearity will restrict the specification for modeling causal mechanisms, preventing the formalization of variables interacting in feedback loops or cascade effects, which are common features in dynamic systems (Sterk et al. 2017). Having an evolving conceptualization of SES based on new empirical studies is also necessary to include emerging or fading interactions, which can serve as a basis for longitudinal studies using panel data. Econometrics can be a way to validate or falsify such evolving interactions.

In addition, spatially explicit studies, although more complex to implement in terms of availability of data and geo-referencing of social dimensions, offer a means to assess SES trajectories at different granular levels and are to be prioritized given the influence of maps on policy makers. Furthermore, the different spatial scales at which interactions between key variables take place can shed additional information on the social–ecological structure of trajectories. While geographic distance can be an important

variable in itself (Díez-Echavarría et al. 2023), the effect that spatial hierarchy has on the agency of stakeholders and on the different spatial granularities of the SES (e.g., household, village, cooperative, catchment or landscape)—as well as the interactions in between these granularities—needs to be considered in the conceptualization of the trajectories. Indeed, while stressors and shocks somehow embeds this spatial hierarchy, it overly simplifies the importance of multi-scalar interactions.

In conclusion, the contributions in this SI illustrate recent development in methods and knowledge to understand complex SES over time and space. All of the studies reflect on trajectories over time, although there is less attention to interactions across different spatial scales. The studies here underscore the importance of, and opportunities for, SES research to explicitly theorize and empirically demonstrate how multi-scalar processes, and their constitutive elements, respond to shocks and stressors and, in turn, influence the long-term trajectories and sustainability of these systems.

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