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Review

Systematic Review of Agent-Based and System Dynamics Models for Social-Ecological System Case Studies

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Abstract: Social–ecological system (SES) modeling involves developing and/or applying models to investigate complex problems arising from the interactions between humans and natural systems. Among the different types, agent-based models (ABM) and system dynamics (SD) are prominent approaches in SES modeling. However, few SES models influence decision-making support and policymaking. The objectives of this study were to explore the application of ABM and SD in SES studies through a systematic review of published real-world case studies and determine the extent to which existing SES models inform policymaking processes. We identified 35 case studies using ABM, SD, or a hybrid of the two and found that each modeling approach shared commonalities that collectively contributed to the policymaking process, offering a comprehensive understanding of the intricate dynamics within SES, facilitating scenario exploration and policy testing, and fostering effective communication and stakeholder engagement. This study also suggests several improvements to chart a more effective trajectory for research in this field, including fostering interdisciplinary collaboration, developing hybrid models, adopting transparent model reporting, and implementing machine-learning algorithms.

Keywords: agent-based model; hybrid model; social–ecological system; system dynamics; case study

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1. Introduction

The current challenges faced by society and the environment are both systemic and managerial [1]. They are systemic because they stem from intricate and interconnected processes that operate at various scales, from local to global, and between various subsystems of the social and ecological realms. These issues cannot be fully comprehended through the lens of a single academic discipline. On the other hand, the issues are managerial because they require concerted and purposeful efforts by policymakers to address them in a sustained and coordinated manner. To address these challenges, a social–ecological systems (SES) approach has emerged that adopts a holistic systemic perspective towards the human and non-human elements [2].

SES refers to the complex and dynamic interrelationships between human societies and the natural environments within which they are embedded [3]. The social component benefits from the services provided by an ecosystem and, in turn, human agency directly or indirectly modifies the functioning and structure of the ecosystem [4]. The central question in SES research is concerned with understanding and managing the complex interactions between humans and nature across different scales and dimensions. This field emphasizes the interdependence and interconnectivity between social and ecological components, recognizing that human actions and decisions can have both positive and negative impacts on the environment and that these impacts can affect human well-being [5]. SES research aims to enhance the resilience and sustainability of human–environment systems [6], which requires the integration of knowledge from different disciplines and perspectives and accounting for uncertainty and feedback [7].

Several operational frameworks have been developed, such as the Panarchy framework, depicting system resilience as an outcome of connected adaptive cycles at different scales [8]; the conceptual cascade framework of "Pattern–Process–Service–Sustainability" that builds on understanding the coupled human and natural system [9]; a social–ecological framework for measuring the contributions of ecosystem services to society [10]; a diagnostic framework to assess the sustainable utilization and management of public resources [3]; a social–ecological action situation framework to analyze the emergence of social–ecological phenomena from system interactions [7]; an analytical framework of regime shifts in social–ecological systems [11]; and three pillars of a sustainability framework that comprise social, economic, and environmental dimensions to provide a holistic perspective, ensuring that the complex interactions between human society and the natural environment are considered [12]. SES frameworks have been used to comprehensively analyze key surface biophysical and socioeconomic processes and set the threshold of a safety boundary that generates more objective results [13].

Although frameworks define interactions and outcomes in SES, they are insufficient for facilitating scenario analysis, which is crucial for generating better social–environmental decisions and policies [14]. Modeling techniques can be applied to simulate several scenarios. Computational models offer a systematic approach for conceptualizing real-world dynamics, the rational consequences of presumptions, past event patterns, and the outcomes of future situations [15]. This may promote stakeholder buy-in by prompting evidence-based decision-making and shifting perceptions of the future to reflect realistic outcomes [16]. Models are increasingly used to test the consequences of alternative assumptions about human behavior [17,18] or social–ecological relations [19] to elucidate the uncertainty associated with the complexity of human behavior and biophysical processes. Dynamic models have been widely used to study SES in various contexts and domains such as water resource management [20], fisheries [21], land use change [22], and urban development [23]. Among the different types, the agent-based model (ABM) and system dynamics (SD) are two prominent approaches in complex system modeling [24].

ABMs simulate the behavior and interactions of individual agents in a system [25]. These models have been used to explore, understand, explain, predict, communicate, illustrate, compare, and mediate social interactions among stakeholders or researchers from different disciplines [26]. ABMs are often used to explore how individual-level behavior can impact the resilience or sustainability of a larger system [27]. Regarding SES, ABMs are commonly employed for three primary purposes: (a) to explore and explain the emergence of social–ecological outcomes and understand how SES evolves over time; (b) to assess the impact of new policies or disturbances on a complex adaptive SES, encompassing potential unintended consequences; and (c) to facilitate participatory processes that enhance the comprehension of issues and collaborative problem-solving [28]. In a SES, agents can represent individuals, households, organizations, and many more. Then, the model can simulate their decisions and interactions in response to environmental or social changes. ABMs have been used for SES modeling in irrigation systems [29], grazing systems [30], and coral reefs [31].

SD simulates the behavior of a system over time, focusing on feedback loops and interactions between different variables [32]. SD modeling offers a set of conceptual, mathematical, and computational resources to address fundamental concepts in SES, such as feedback loops, nonlinear relationships, and regime shifts. SD modeling has been applied to explore the interconnections between system components, explicit representation of system-level dynamics through causal relationships, and responses of a SES to policy interventions and external forces [33]. In a SES, SD can be used to explore the impacts of policy interventions or environmental changes on the overall system, identify leverage points for intervention, and for other applications [27]. SD has been used to model SES in lake restoration [27], forest management [34], and coastal fisheries [35].

The value of SES modeling is largely determined by its applicability for understanding and interpreting real-world case studies [36]. Case studies, which are widely used in SES research, can capture the diversity and complexity of SES by examining specific contexts that illustrate general patterns or principles [3]. In addition, case studies can identify the key variables, indicators, drivers, outcomes, trade-offs, synergies, thresholds, and resilience of a SES and aid in developing sustainable policies and interventions [3,27].

SES modeling is emerging as a prominent research area, though it lacks appropriate research integration and synthesis [37]. Previous reviews explored the modeling of the SES framework to identify the challenges [38], recommendations for good practice [39], strategies to advance reporting [40], and methodological guidelines for future applications [41]. However, there has been no focused review on the integration of ABM or SD modeling outcomes in a particular case study related to the SES, specifically in the context of aiding the policymaking process. Consequently, only a few SES models have influenced decision support and policymaking compared to models from other areas such as transportation planning, epidemiology, and pesticide risk assessment [42–44].

This study aimed to explore the application of ABMs and SD in SES modeling through a systematic review of published real-world case studies and determine the extent to which existing SES models influence policymaking. We also explored the key characteristics of both modeling approaches for elucidating the complexity of the SES. Our comprehensive review elucidates the common factors associated with the improved integration of models into the policymaking process.

2. Materials and Methods

A systematic review of peer-reviewed literature was performed on 3 April 2023, using the scholarly databases Dimensions and Web of Science. We conducted a systematic review consistent with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [45] through four main steps (Figure 1).

2.1. Step 1: Systematic Literature Search in Dimensions and Web of Science

We searched for literature that modeled the SES framework using ABMs or SD in any real-world case study within the last 10 years. Although system modeling, both ABM and SD, and the idea of combining them are not new and date back to the late 1990s [46], we limited our article search only to the last 10 years to ensure that the review is an up-to-date, comprehensive, and insightful analysis of the most recent research in the field. Both databases were searched using the following search terms in the title, abstract, and keywords fields: ("social–ecological system" AND "system dynamics" AND model*) for SD, and ("social–ecological system" AND "agent-based" AND model*) for ABMs.

2.2. Step 2: Screening of the Search Results

The list was refined by excluding duplicates, review articles, non-English articles, and articles without abstracts. The list was then manually refined by reading the abstracts and full text to check for applicability within the scope of this study. A study was considered eligible if it applied ABMs or SD to SES modeling within a case study.

2.3. Step 3: Coding of Included Publications for Data Collection

Each included article was read, evaluated, and coded using standardized criteria. In addition to the bibliometric information (i.e., author, title, year, and DOI), we collected complementary information by reviewing the abstract and full text of the final articles and coding them against four key aspects.

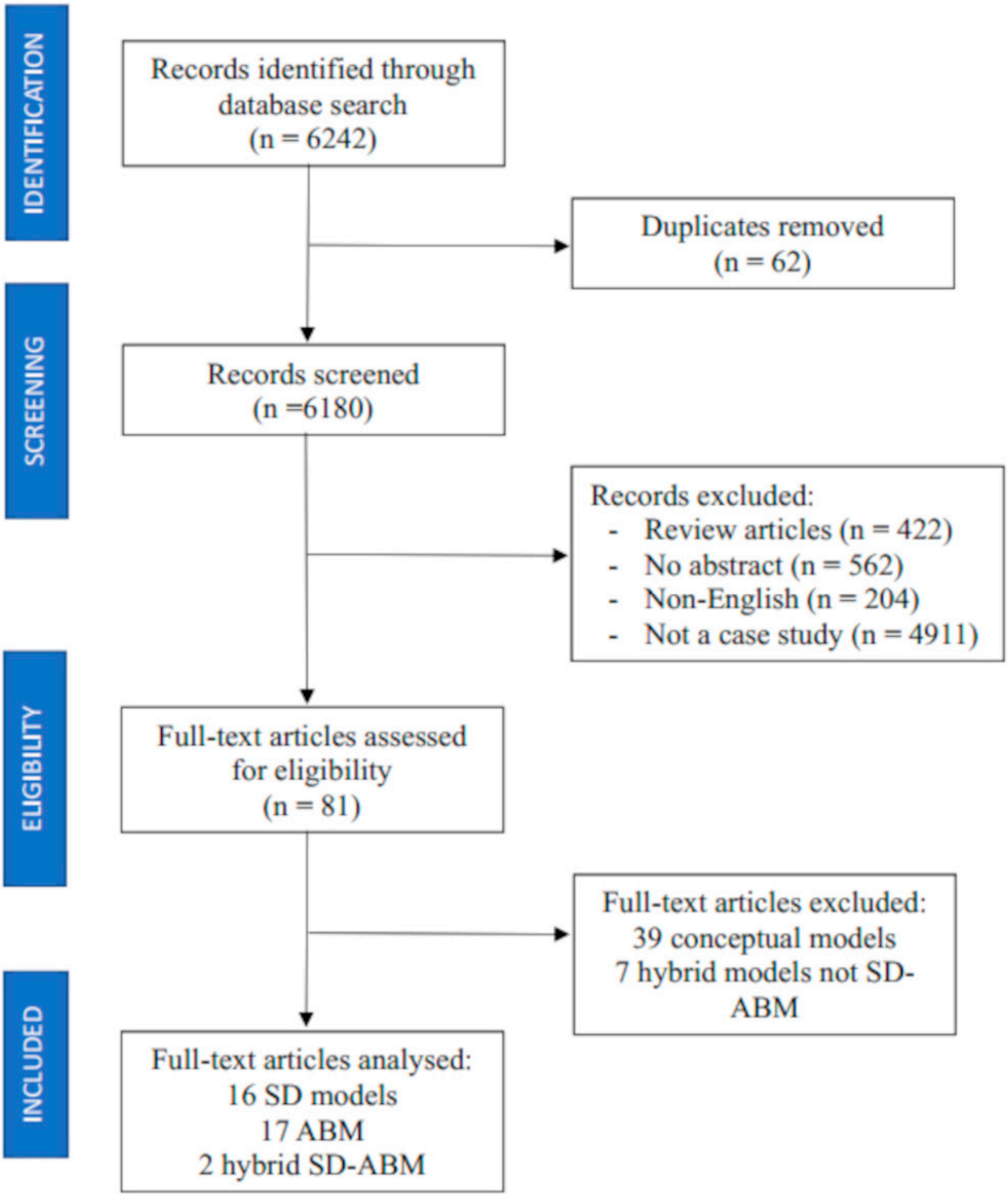

Figure 1. A PRISMA diagram of the identification and selection of studies.

2.3.1. Aspect 1: Geographical Characteristics

Every SES requires a suitable system boundary to effectively identify management implications and facilitate comparisons [47]. This is crucial because a SES should encompass the relevant ecological systems essential for maintaining key biophysical structures and processes. In doing so, the SES can provide ecosystem services and support social systems, including individuals and administrative bodies [48]. To identify spatial boundaries, the articles were classified into four categories: local, regional, national, and international [49]. In addition, the articles were classified based on their location, being in high-, upper middle-, lower middle-, or low-income countries, as previously described [50], to assess the difference in SES application between developing and developed countries.

2.3.2. Aspect 2: SES Component Being Modeled

The characterization of a SES model aids in elucidating its intricate nature at a moderate level of abstraction between specific case studies and general theories, thereby facilitating a comparison and generalization of knowledge [51]. In this study, the SES models were characterized based on a conceptual framework (Figure 2) structured into 13 dimensions distributed throughout the three main components of a SES: the social system, ecological system, and interactions between them [52]. A list of variables for each dimension is presented in Table 1. This framework has two advantages. First, it is simple to understand by dividing the SES into three components that have several dimensions and variables. Second, this framework is quite general, making it suitable to describe the diverse SES model.

Figure 2. A conceptual framework for characterizing the SES model (adopted from Pacheco-Romero et al. [52]).

Table 1. List of variables for each dimension of SES components [52].

Component	Dimension	Variables
Social	Human population dynamics	population size, density, distribution, migration, etc.
	Well-being and development	employment, income, educational level, wealth distribution, etc.
	Governance	stakeholder participation, political stability, government capacity, etc.
Ecological	Organic carbon dynamics	primary productivity, biomass, ecosystem composition, etc.
	Water dynamics	precipitation, evaporation, soil water storage, etc.
	Surface energy balance	solar radiation, air temperature, land surface temperature, heat flux, etc.
	Nutrient cycling	nutrient fixation, nutrient deposition, nutrient availability, etc.
	Disturbance regime	drought, flood, storm, landslide, etc.
Interactions	*E → S: the ecological components influence the social components*	
	Ecosystem service supply Ecosystem disservice supply	agricultural and livestock production, pest control, bioremediation, etc. soil erosion, red tides, pathogens, etc.
	E ← S: human activities affect the ecological components	
	Ecosystem service demand Human actions on the environment	nature tourism, appropriation of land for agriculture, water and energy usage, etc. land use change, territorial connectivity, pollution, conservation, protected area, etc.
	E ↔ S: the reciprocity between the social components and ecological components is considered	
	Social–ecological coupling	renewable energy use, biocapacity, land tenure, etc.

2.3.3. Aspect 3: Stakeholder Involvement

The involvement of stakeholders could be underpinned in several ways, including through normative arguments (participation is a democratic right), substantive arguments (involvement produces better knowledge), instrumental arguments (participation improves the chance of success), and transformative arguments (improvement of social capital) [53].

Regardless, stakeholder involvement is critical for an impactful modeling endeavor [54]. Given the increasing role of stakeholders in co-developing SES models, the type and extent of stakeholder participation in the reviewed studies were categorized as non-participatory, participation in model development, participation in model use, and participation in both model development and use.

2.3.4. Aspect 4: Practical Application from the Model

The practical application of SES models in the policymaking process can be evaluated based on their relevance to policy decision-making and legislative changes [15]. If the model outcomes were relevant to policy decision-making or led to legislative changes, they represented a "high" level of practical application. In contrast, if the models primarily stimulate discussion and generate understanding without directly influencing policy decision-making, they were considered to have a "low" practical application [54]. Furthermore, these models must have a user-friendly interface that effectively captures the complexity of the final models. This interface should be intuitive and easily navigable for end users to independently utilize the model [55]. By ensuring user-friendliness, the model becomes more accessible for practical applications.

2.4. Step 4: Summary and Analysis of Collected Data

The identification of common factors would provide insights for future applications while also positing critical reflections on the limitations of current approaches. A comparative analysis of the reviewed literature was conducted to assess the potential applicability of the ABMs and SD of SES in the policymaking process. This involved summarizing and analyzing the four aspects across all articles using descriptive statistics and diagrams in Microsoft Excel (Microsoft 365 Apps for enterprise) and Quantyl Discovery (version 2.0).

3. Results

From the initial pool of 6242 papers, 81 were chosen for comprehensive full-text screening. Finally, 35 articles met the inclusion criteria, including 16 papers utilizing SD, 17 utilizing ABM, and two employing a hybrid SD–ABM approach. Appendix A provides the full details of the coding for the four key aspects.

3.1. Aspect 1: Geographical Characteristics

Concerning spatial scale, most studies (60%) focused on the regional scale, primarily addressing the management of natural resources [30,56–67], regional development [68–70], and environmental resilience [71–75]. Local-scale investigations constituted the second most common focus (31%), with an emphasis on enhancing local sustainability in response to high vulnerability arising from both natural [76,77] and anthropogenic threats [27,78–85]. Case studies on a national scale were less prevalent (9%), and no studies were conducted on an international scale. Regarding geographical distribution, the reviewed papers predominantly presented case studies from high-income countries (57%), with fewer studies conducted in upper- and lower-middle-income countries (23% and 17%, respectively). Only one study was conducted in a low-income country.

Figure 3 shows the distribution of the study scales in relation to the income levels of the countries. Regional-scale studies have been conducted across all types of countries. Local-scale investigations were primarily concentrated in high- and upper-middle-income countries, whereas national-scale studies were more prevalent in upper- and lower-middle-income countries.

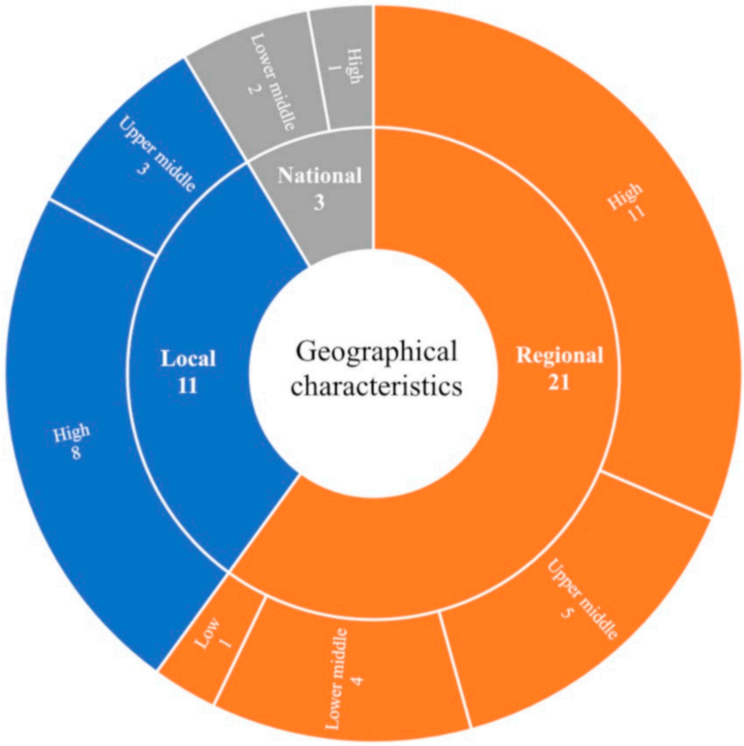

Figure 3. Study scale based on the level of income.

3.2. Aspect 2. SES Component Being Modeled

Among the 13 dimensions encompassing the SES components, ABMs encompassed 10, albeit with varying degrees of emphasis (Figure 4a). Within the social component, particular attention was directed towards the well-being and development (WBD) dimension, whereas the governance (G) and human population dynamics (HPD) dimensions received limited consideration. Regarding the ecological component, considerable emphasis was placed on both organic carbon dynamics (OCD) and water dynamics (WD). In contrast, the nutrient cycling (NC) and disturbance regime (DR) dimensions were less prevalent, and the surface energy balance dimension was absent across the studies examined. SES interaction components exhibited nuanced patterns. Notably, ecosystem service supply (ESS) and human action on the environment (HAE) shared a substantial proportion of the interactions, signifying their interconnected nature. The ecosystem service demand (ESD) dimension occupied the remaining portion, whereas the ecosystem disservice supply (EDS) and social–ecological coupling (SEC) dimensions were absent from the analyzed studies. Furthermore, the strong representation of the ESS and HAE dimensions facilitates a cohesive linkage between the social and ecological components. These dimensions effectively bridge the interaction between the human and ecological facets of the system, highlighting their intricate interdependence and underscoring the role of ABMs in capturing these vital connections within the SES.

SD incorporated 12 of the 13 intrinsic SES dimensions, albeit with varying degrees of emphasis (Figure 4b). Within the social component, the WBD and HPD dimensions were prominent and shared comparable representation, while the G dimension constituted the remaining portion of the social facet. Regarding the ecological component, the OCD dimension comprised 50%, the NC and WD dimensions shared 40%, while the DR dimension encompassed the remaining portion. Similar to the ABM findings, the surface energy balance dimension was absent. Within the interaction component, the SD prominently featured both the ESS and HAE dimensions, sharing nearly equivalent proportions. The ESD, EDS, and SEC dimensions collectively accounted for the remaining share. Notably, the ESS and HAE dimensions demonstrated a superior capacity for linking social and ecological components, underscoring their pivotal role in enhancing cross-component interactions within the SES.

The hybrid SD–ABM approach, applied in two articles, encompassed 7 of the 13 dimensions (Figure 4c). WBD and HPD predominated the social component; OCD, NC, and WD predominated the ecological component; and HAE and EDS predominated the interaction component. The hybrid SD–ABM approach effectively integrated these dimensions, contributing to a more comprehensive understanding of the intricate interplay between the social and ecological elements within the SES.

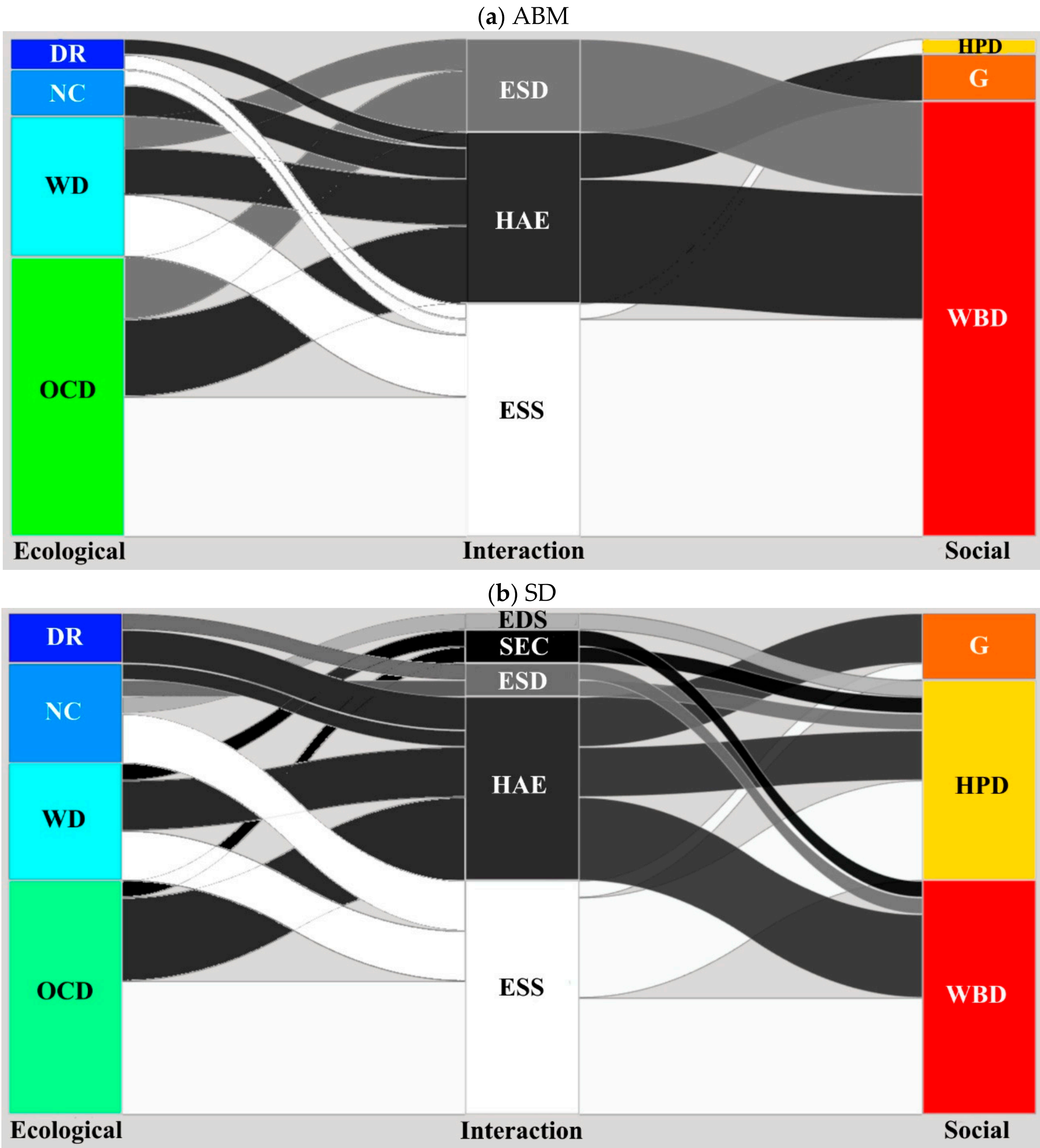

Figure 4. *Cont.*

(c) Hybrid

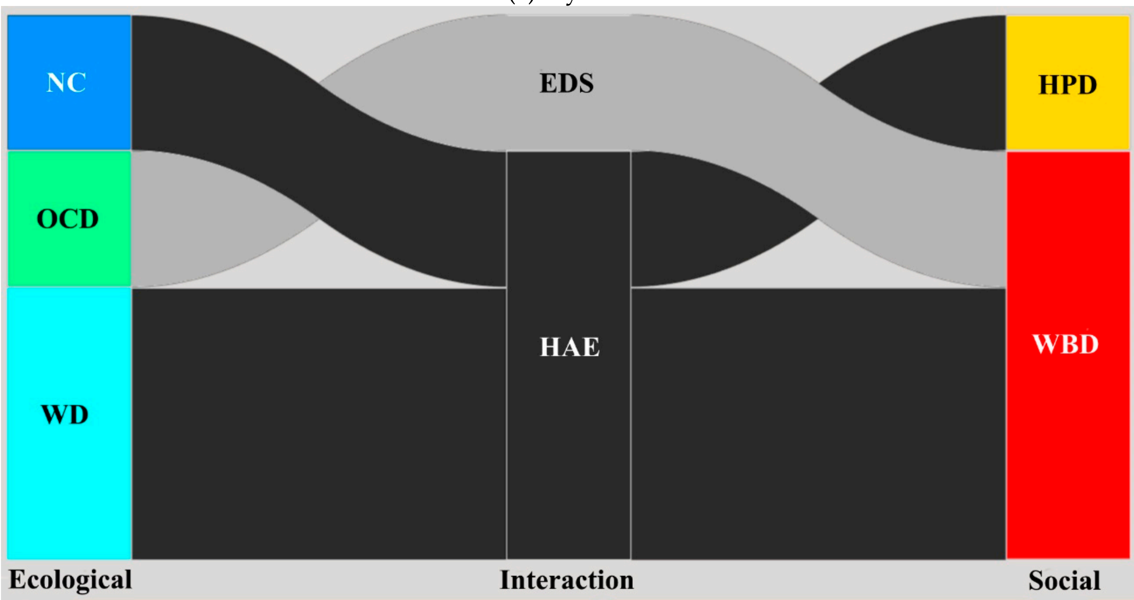

Figure 4. Alluvial diagrams showing the relationship between social and ecological systems by model type. (**a**) ABM, (**b**) SD, and (**c**) hybrid SD–ABM. Abbreviations: DR = disturbance regime; NC = nutrient cycling; WD = water dynamics; OCD = organic carbon dynamics; HPD = human population dynamics; G = governance; WBD = well-being and development; ESS = ecosystem service supply; ESD = ecosystem service demand; HAE = human action on the environment; EDS = ecosystem disservice supply; SEC = social–ecological coupling.

3.3. Aspect 3: Stakeholder Involvement

Table 2 shows the number of studies reviewed based on stakeholder involvement and modeling techniques. While stakeholder involvement is pivotal to the success of modeling endeavors [54], half of the reviewed articles (49%) did not incorporate stakeholders into their modeling processes. This omission can be attributed to the inherent technical intricacies of certain models, necessitating specialized knowledge that stakeholders may lack, potentially constraining the value of their participation [63,67,71,78,81]. The importance of stakeholder involvement is often constrained in models that focus on ecological systems [64,72,73,79,83,85]. Moreover, time and resource constraints, particularly for national-level studies [86,87] spanning jurisdictional boundaries [65] or requiring extensive data inputs [82], can render meaningful stakeholder engagement impractical. Interestingly, Bitterman and Bennett [76] noted that involving stakeholders could potentially enhance their models in future work.

Table 2. Number of articles based on stakeholder involvement and modeling technique.

	Modeling Technique		
Stakeholder Involvement	**ABM**	**SD**	**Hybrid SD–ABM**
None	8	8	1
Model development	7	4	0
Model use	1	3	0
Model development and use	1	1	1

In the remaining articles, we observed notable variations in the extent of stakeholder engagement. Within this subset, 31% of the articles engaged stakeholders during model development to delineate problems and set boundaries, 11% incorporated stakeholders into the application phase to validate the model outcomes and ensure the robustness of the results through negotiation, and 9% embraced stakeholder involvement in both model development and application.

Analyzing the prevalence of stakeholder engagement in relation to system modeling techniques revealed pertinent insights. Among the reviewed articles employing SD, half (50%) did not integrate stakeholders into the modeling process. Conversely, the remaining 50% demonstrated diverse degrees of stakeholder involvement: 25% during model development, 19% during model application, and 6% during both the development and application phases. A parallel examination of articles employing ABMs revealed that 47% did not engage stakeholders, 41% involved stakeholders during model development, 6% during model application, and 6% during both phases. Of the two articles employing the hybrid SD–ABM approach, one abstained from stakeholder involvement, while the other embraced stakeholders during both model development and application.

3.4. Aspect 4: Practical Application from the Model

Table 3 lists the number of studies using practical applications and modeling techniques. The utility of SES models in the decision-making process was evident as 54% of the articles demonstrated a notable level of practical applicability. A defining attribute of system modeling is its capacity for scenario analysis through simulation, yielding quantifiable policy recommendations. This capability was effectively harnessed by a subset of the reviewed articles, with nine utilizing SD, eight employing ABMs, and two adopting a hybrid SD–ABM approach to highlight the advantageous outcomes achievable through scenario-based analyses.

Table 3. Number of reviewed articles based on modeling technique and practical application.

	Modeling Technique		
Practical Application	**ABM**	**SD**	**Hybrid SD–ABM**
High	8	9	2
Low	9	7	0

Within this cohort of 19 articles, only 5 incorporated a user-friendly interface, which has a considerable impact on model application by policymakers. Accessible interfaces empower policymakers and promote the effectiveness of the modeling endeavor, bolstering the role of SES models as a robust tool for evidence-based policy formulation and implementation and promoting informed engagement for harnessing the full analytical capabilities of SES models to meet the nuanced demands of real-world policy contexts. Consequently, the judicious inclusion of user-friendly interfaces amplifies the practical applicability of SES models and empowers policymakers to leverage their potential for shaping sustainable and effective policy outcomes.

4. Discussion

Our systematic review of research articles utilizing the SD, ABM, and hybrid SD–ABM approaches for SES modeling provides valuable insights into the potential contributions of these approaches to policymaking. By analyzing the breakdown of the models into social, ecological, and interaction components, we compared their strengths, weaknesses, and commonalities and elucidated the role of each modeling technique in enhancing our understanding of SES dynamics.

4.1. Strengths and Limitations of ABMs

Most ABMs with a high level of applicability focus extensively on the well-being and development dimensions within the social component. Its unique capacity to capture individual-level interactions and decision-making processes enables the simulation of agents' strategies for optimizing yields and income [57–59,69,86]. This granularity extends to the ecological component, where ABMs excel in depicting organic carbon and water dynamics. The model's proficiency in simulating intricate ecological processes, ranging from species movement to groundwater resource dynamicsprovides valuable insights [57,59,61,62,64]. Notably, ABMs effectively represent human actions in the environmental dimension, stemming from its inherent focus on emergent behaviors arising from agent interactions. This capacity aligns seamlessly with the modeling of human efforts in shaping their surroundings through activities such as land-use alterations, conservation initiatives, and restoration programs [57,61,64,80,86]. Furthermore, ABMs offer insights into the drivers, changing processes, and spatial characteristics within a SES, particularly through the simulation of individual agent interactions [30]. In addition, ABMs can effectively inform managers about the trade-offs inherent in complex and diverse policy decisions by modeling individual heterogeneity, which is crucial for quantitatively evaluating the consequences of policies [65,74].

However, it is important to recognize that ABMs, while a powerful tool, should not serve as the sole determinant of policymaking, because complex social, political, and ecological aspects may not be adequately addressed by simulations alone [65]. Moreover, the high computational demands of ABMs, particularly in complex or large-scale scenarios, can restrict its real-time application in policy analysis and decision-making processes [81]. These demands, coupled with data limitations, can inadvertently hinder comprehensive stakeholder involvement, which is a key factor in successful policy integration [59].

4.2. Strengths and Limitations of SD

Conversely, SD exhibits a balanced representation across all SES components, with a notable emphasis on organic carbon dynamics, well-being and development, ecosystem service supply, and human actions on the environment. The ability of SD to capture feedback loops and dynamics renders it applicable for modeling nearly all SES dimensions, indicating its usefulness in elucidating the feedback mechanisms between social and ecological systems [87]. Understanding these feedback mechanisms could inform the development of a holistic framework for SES management by facilitating the effective communication of scientific results to managers and guiding environmental decision-making through objective comparisons of different management options [75]. Moreover, SD can integrate disparate data types over extended time periods, uncover robust connections between human and natural subsystems, and provide flexibility in exploring alternative scenarios [56].

The capacity to aggregate and average variables enhances the applicability of SD in modeling large-scale interactions and offers a high-level perspective on system behavior. However, this aggregation process can lead to oversimplification of complex interactions, potentially neglecting crucial system intricacies [82]. It is important to acknowledge that, while versatile, SD should be applied with caution to avoid oversimplifying complex socio-ecological dynamics [88]. SD also faces challenges in terms of time-series data availability [84].

4.3. Strengths and Limitations of the Hybrid SD–ABM

Hybrid models are emerging methodologies that combine the strengths of SD and ABMs, thereby facilitating the integration of macro-level dynamics with micro-level individual behaviors [26]. Three methods exist for constructing a hybrid SD-ABM model: integrated, interfaced, and sequential hybrid designs [89]. In integrated hybrid models, ABM and SD merge, allowing ABM and SD to interact simultaneously. Interfaced hybrids feature independent ABM and SD models exchanging data at designated simulation points. Sequential hybrids run ABM and SD separately, with one's output becoming the other's input. Both reviewed articles utilized the integrated hybrid design. Although the hybrid approach enhances the modeling of SES, the complexity introduced by the hybrid models can challenge stakeholder involvement because of the need to understand both modeling paradigms. As the demand for models that capture macro- and micro-level SES dynamics grows, the use of hybrid models is anticipated to increase.

4.4. Commonalities

Having their own strengths and limitations, these three modeling approaches share commonalities that collectively contribute to the policymaking process.

4.4.1. Comprehensive Insight and Integration

Our systematic review demonstrated that all three modeling approaches offer a comprehensive understanding of the intricate dynamics within SES. ABM could depict emergent behaviors arising from interactions among agents, offering valuable insights into the complex adaptive mechanisms within an SES. On the contrary, SD is better at grasping feedback loops and dynamics, demonstrating its effectiveness in unraveling the complex feedback mechanisms between social and ecological systems. Using these models, policymakers can gain a holistic view of how social and ecological components interact and influence each other. This integrated perspective provides a foundation for decision-making, allowing policymakers to recognize the complex relationships among human actions, ecological responses, and overall system behavior. The ability of these models to identify critical drivers and feedback loops further enriches this understanding, enabling policymakers to pinpoint areas in which interventions can be most effective and anticipate potential system responses. By capturing the interdependencies between social and ecological dimensions, these approaches emphasize the inseparable nature of human and natural dynamics in SES, urging policymakers to consider both facets simultaneously in policy formulation.

4.4.2. Policy Evaluation and Decision Support

One of the notable strengths shared by the SD, ABM, and hybrid SD–ABM is their capacity to facilitate scenario exploration and policy testing. These models allow policymakers to simulate a wide range of scenarios and policy interventions, offering a controlled environment for assessing potential outcomes, trade-offs, and unintended consequences. Furthermore, these approaches generate quantitative insights that enable objective data-driven decision-making. By incorporating empirical data and quantitative analysis, policymakers can formulate evidence-based strategies to increase the likelihood of achieving the desired policy outcomes. This quantitative approach also enables the assessment of trade-offs and synergies among various policy options, ensuring that policies are both effective and balanced in addressing the multiple dimensions of SES.

4.4.3. Effective Communication and Engagement

In addition to providing insights and decision-making support, the SD, ABM, and hybrid SD–ABM offer a suite of tools that foster effective communication and stakeholder engagement. Through visualization and scenario analysis, these models translate complex system dynamics into accessible visual representations, enabling policymakers to communicate trends, relationships, and potential policy impacts more effectively. This visualization aids in engaging stakeholders, including policymakers, communities, and interest groups, by offering a tangible platform for understanding the implications of different policy choices. Furthermore, the iterative nature of the models promotes adaptive management and learning. Policymakers can observe how a system responds to various interventions, thereby encouraging a dynamic and responsive approach to policy formulation. By involving stakeholders throughout the modeling process, from development to application, policymakers can ensure that decisions are informed by diverse perspectives, enhancing the legitimacy and acceptance of policies within the broader community.

4.5. Implications for Future Research

This review highlights the major achievements in the field of SES modeling in case studies employing SD and ABM. These modeling approaches have provided valuable insights into the complex dynamics of SES and their implications for policymaking. However, this analysis has certain limitations in current modeling paradigms. To advance the field and harness the full potential of ABM and SD for SES modeling, we provide several suggestions for future directions in this research field.

First, interdisciplinary collaboration among researchers should be fostered to improve data availability for model formalization. In this context, participatory modeling approaches would be valuable. Interdisciplinary teams and stakeholders can leverage diverse knowledge and perspectives to advance the capabilities of the models and ensure their relevance and applicability. Second, the integration of the ABM and SD approaches within hybrid models shows promise. The synergy between an ABM's micro-level focus on individual behaviors and SD's macro-level systemic insights can provide a more comprehensive understanding of SES dynamics. This hybridization can help overcome the oversimplification in SD models by capturing the finer details of interactions and behaviors. However, hybrid models can be more complex and less accessible to non-experts. To address these challenges, transparent model documentation and reporting practices should be developed to clearly outline how the SD and ABM components interact, which would enhance the credibility and replicability of the model. Finally, implementing machine learning (ML) algorithms in the ABM and SD can enhance their performance in modeling SES. In ABMs, ML algorithms can be used to develop more sophisticated agent behaviors and decision-making rules, whereas agents can learn from their interactions with the environment and other agents, allowing for the representation of adaptive and evolving behaviors [90]. In SD, ML algorithms can be used to optimize model parameters, which can be particularly valuable in scenarios where finding the best parameter values is challenging [91]. This optimization can promote the fit of empirical data and real-world observations to these models. Furthermore, ML algorithms can automate the generation and exploration of a wide range of scenarios in both ABMs and SD. This can help researchers and policymakers more efficiently assess the potential impacts of different policy interventions, management strategies, and environmental changes.

4.6. Limitations of This Study

While we acknowledge the crucial role of handling uncertainty in modeling, it should be noted that the inclusion of this aspect was not explicitly detailed in our review. We assumed that managing uncertainty is a standard practice in modeling, recognizing its significance in the robustness and reliability of model outcomes. However, it is imperative to recognize that addressing uncertainty can vary significantly based on the specific context, the nature of the uncertainty (such as parameter uncertainty or model structure uncertainty), and the objectives of the modeling exercise. Given the diverse and context-dependent nature of uncertainty-handling techniques, we chose to exclude this aspect from our review. This exclusion, therefore, represents a limitation of our study, highlighting the complexity and variability inherent in addressing uncertainty within the realm of SES modeling. Future research endeavors could delve into this critical dimension, exploring the nuanced techniques and methodologies employed in managing uncertainties to further enrich the understanding of modeling practices in the domain of SES.

Another limitation of our study is the depth of exploration into participatory modeling methodologies. Although our categorization encompassed various levels of stakeholder involvement in model development and utilization, we overlooked specific techniques such as mediated and companion modeling. Mediated modeling, where the modeler acts as a mediator between stakeholders and the model, and companion modeling, which emphasizes collaborative model construction, offer more profound insights through active stakeholder engagement. Thus, future research should delve deeper into these advanced participatory modeling approaches to offer a more comprehensive perspective on stakeholder involvement in modeling SES.

5. Conclusions

This study reviewed SD and ABM applications in the modeling of SES through case studies. The findings revealed that each modeling approach captured the multifaceted dynamics of SES. We outlined the strengths and limitations of the ABM and SD for SES modeling in real-world scenarios, which provides valuable insights for future directions in this domain.

Author Contributions: Conceptualization, S.N.; Investigation, S.N.; Resources, S.N. and T.U.; Data curation, S.N.; Formal analysis, S.N.; Methodology, S.N.; Writing—original draft, S.N.; Writing—review and editing, T.U.; Visualization, S.N.; Supervision, T.U.; Project Administration, T.U.; Funding acquisition, T.U. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: All the data are provided in the Appendix A.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Summary of reviewed articles.

Author	Year	DOI	Title	Geographical Characteristics		SES Components Being Modeled			Stakeholder Involvement	Practical Application
				Location	Spatial Scale	Ecological Subsystem	Social Subsystem	Interactions		
ABM										
Leahy, Jessica E.; Reeves, Erika Gorczyca; Bell, Kathleen P.; Straub, Crista L.; Wilson, Jeremy S.	2013	10.1155/2013/563068	Agent-Based Modeling of Harvest Decisions by Small Scale Forest Landowners in Maine, USA	1: High	1: Local	(1) Forest consisting of hardwood, softwood, and mixed trees	(2) Landowner strategies to increase income	(1) E → S: Timber production and other forest products generate income for landowners (3) E ← S: Nature tourism as an alternative source of income for landowners	1: None	Simulated harvesting scenarios (heavy, light, and combined). Did not provide policy recommendation, but improved understanding of small-scale timber harvesting behavior.
Yan, Huimin; Pan, Lihu; Xue, Zhichao; Zhen, Lin; Bai, Xuehong; Hu, Yunfeng; Huang, He-Qing	2019	10.3390/su11082261	Agent-Based Modeling of Sustainable Ecological Consumption for Grasslands: A Case Study of Inner Mongolia, China	2: Upper middle	2: Regional	(1) Net primary productivity of grasslands	(1 and 2) Population dynamics and the sheep and cattle breeding activities of herders	(1) E → S: Livestock production depends on grasslands	2: Model development	Simulated four scenarios to forecast herder behavior and ecosystem pressures for the next 30 years. Did not provide policy recommendation, but improved understanding of the impact of herders on grassland ecosystem.
Huber, Robert; Briner, Simon; Peringer, Alexander; Lauber, Stefan; Seidl, Roman; Widmer, Alexander; Gillet, François; Buttler, Alexandre; Le, Quang Bao; Hirschi, Christian	2013	10.5751/es-05487-180241	Modeling Social–Ecological Feedback Effects in the Implementation of Payments for Environmental Services in Pasture-Woodlands	1: High	1: Local	(1 and 4) Pasture-woodland ecosystem consisting of herbs (eutrophic pastureland, oligotrophic pastureland, and fallow field), shrubs, and trees (13 species); their distribution depends on soil characteristics and nutrient availability.	(2) Farmer strategies to optimize income from livestock activities and remuneration for keeping wooded pastures.	(1) E → S: Livestock production depends on fodder from pasture–woodlands (4) E ← S: Conservation policy to maintain silvopastoral landscapes	2: Model development	Simulated and compared two conservation policies, i.e., protection and payment for environmental services. Payment for environmental services could conserve biodiversity in wooded pastures.
Williams, Benjamin C.; Criddle, Keith R.; Kruse, Gordon H.	2019	10.1111/nrm.12305	An agent-based model to optimize transboundary management for the walleye pollock (*Gadus chalcogrammus*) fishery in the Gulf of Alaska	1: High	2: Regional	(1) Fish population dynamics	(2) Fisherman strategies to maximize revenue	(1) E → S: Annual harvest of walleye pollock (4) E ← S: Manager strategies to sustain fishery	1: None	Simulated several management scenarios. Did not produce a policy recommendation, but informed managers on the trade-offs present in complex and diverse policy decisions using ABMs.

Table A1. *Cont.*

Author	Year	DOI	Title	Geographical Characteristics		SES Components Being Modeled			Stakeholder Involvement	Practical Application
				Location	Spatial Scale	Ecological Subsystem	Social Subsystem	Interactions		
ABM										
Anbari, Mohammad Javad; Zarghami, Mahdi; Nadiri, Ata-Allah	2021	10.1016/ j.agwat.2021.106796	An uncertain agent-based model for socio-ecological simulation of groundwater use in irrigation: A case study of Lake Urmia Basin, Iran	3: Lower middle	2: Regional	(2) Groundwater resource dynamics	(2 and 3) Farmer strategies to maximize income and government policy to increase efficiency in agricultural sector	(1) E → S: Agricultural production depends on groundwater resources (4) E ← S: Government policy to prevent degradation of aquifer and increase efficiency in agricultural sector	2: Model development	Simulated several management scenarios, e.g., well monitoring, license adjustment, and promoting efficient irrigation technology. Provided quantified policy recommendations to prevent aquifer degradation.
Martin, R.	2014	10.1016/ j.envsoft.2014.10.012	Livelihood security in face of drought—Assessing the vulnerability of pastoral households	3: Lower middle	2: Regional	(1, 2, and 5) Perennial vegetation consisting of green and wood biomass, which is influenced by precipitation and drought occurrence.	(2) Pastoralist strategies in maintaining a minimum viable herd size each year.	(1) E → S: Livestock production affected by forage availability and drought occurrence	1: None	Simulated climate variability to study its impact on pastoral household vulnerability. Did not provide any policy recommendations but some valuable insights on the external shocks (i.e., drought) and their relevance as driving forces for systematic changes in SES.
Bitterman, P., and Bennett, D.A.	2016	10.5751/ ES-08677-210321	Constructing stability landscapes to identify alternative states in coupled social–ecological agent-based models	1: High	1: Local	(5) Droughts and floods create landscape perturbations	(2) Farmer adaptation strategies to managing their farm to gain revenue	(1) E → S: Crop production (corn, soybean, or switchgrass) (2) E → S: Soil erosion (4) E ← S: Land use change as form of adaptation to perturbation	1: None	Simulated several scenarios evaluating farmer resilience to perturbation regime. Did not provide any policy recommendations.
Huber, L., Rüdisser, J., Meisch, C., Stotten, R., Leitinger, G., and Tappeiner, U.	2021	10.1016/ j.scitotenv.2020.142962	Agent-based modelling of water balance in a social–ecological system: A multidisciplinary approach for mountain catchments	1: High	2: Regional	(2) Water resource dynamics in mountain catchment area from precipitation and evapotranspiration	(2) Competition between water users, including farmers, inhabitants, hotels, and a hydro-powerplant.	(3) E ← S: Water usage could lead to water scarcity, based on high water demand:supply ratio	3: Model use	Simulated several scenarios to assess impact of climate change on water scarcity in mountainous regions. Provided policy recommendations and a user-friendly interface for stakeholders and decision-makers to interact with the model.

Table A1. *Cont.*

Author	Year	DOI	Title	Geographical Characteristics		SES Components Being Modeled			Stakeholder Involvement	Practical Application
				Location	Spatial Scale	Ecological Subsystem	Social Subsystem	Interactions		
ABM										
Cenek, M., and Franklin, M.	2017	10.1016/ j.ecolmodel.2017.06.024	An adaptable agent-based model for guiding multi-species Pacific salmon fisheries management within a SES framework	1: High	1: Local	(4) Amino-acid availability affecting salmon movement to spawning tributaries	(2) Fisherman happiness affected fishing effort	(1) E → S: Salmon yield affected fishermen income (4) E ← S: Manager action to conserve salmon by opening or closing the fishing zone	1: None	Simulated manager action in opening or closing the fishing zone to promote salmon escapement rate. Did not produce a policy recommendation but filled knowledge gap in the use of ABMs for accurately simulating fishery dynamics.
Innes-Gold, A.A., Pavlowich, T., Heinichen, M., McManus, M.C., McNamee, J., Collie, J., and Humphries, A. T	2021	10.5751/ ES-12451-260240	Exploring social–ecological trade-offs in fisheries using a coupled food web and human behavior model	1: High	2: Regional	(1) Fish population dynamics	(2) Fisherman satisfaction dictated participation in fishery	(1) E → S: Commercial forage fish harvest (3) E ← S: Recreational fishing of piscivorous fish	1: None	Simulated several harvest scenarios to explore trade-offs between commercial and recreational fisheries. Did not provide policy recommendation but a reproducible yet flexible methodology for incorporating human behavior in SES models.
Schouten, M., Opdam, P., Polman, N., and Westerhof, E.	2013	10.1016/ j.landusepol.2012.06.008	Resilience-based governance in rural landscapes: Experiments with agri-environment schemes using a spatially explicit agent-based model	1: High	2: Regional	(1) Primary productivity of rural landscape affected by soil quality, groundwater availability, and land cover diversity	(2) Farmer decision in obtaining revenue by producing milk or joining agri–environment scheme	(1) E → S: Milk production (4) E ← S: Government policy to conserve biodiversity by providing incentive for farmers that join agri-environment scheme	1: None	Simulated two policy scenarios, i.e., fixed and flexible payment of AES. Flexible payment of AES could increase resilience in rural landscape, i.e., the biodiversity became less sensitive to large-scale disturbances.
Brinkmann, K., Kübler, D., Liehr, S., and Buerkert, A.	2021	10.1016/ j.agsy.2021.103125	Agent-based modelling of the social–ecological nature of poverty traps in southwestern Madagascar	4: Low	2: Regional	(2) Precipitation as predictor of soil fertility	(2) Household strategies to optimize income and attain food self-sufficiency	(1) E → S: Agricultural and livestock production (3 and 4) E ← S: Household attempt to increase crop yield and income could drive land use and cover change	2: Model development	Simulated two crop management strategies to explore the effect of crop management improvement on households avoiding the social-ecological trap. Did not provide any policy recommendations but provides support for discussion with local stakeholders to determine land productivity, food security, and well-being.

Table A1. *Cont.*

Author	Year	DOI	Title	Geographical Characteristics		SES Components Being Modeled			Stakeholder Involvement	Practical Application
				Location	Spatial Scale	Ecological Subsystem	Social Subsystem	Interactions		
ABM										
Gonzalez-Redin, J., Polhill, J.G., Dawson, T.P., Hill, R., and Gordon, I.J	2020	10.1007/s13280-019-01286-8	Exploring sustainable scenarios in debt-based social–ecological systems: The case for palm oil production in Indonesia	3: Lower middle	3: National	(1) Land-cover types grouped in protected areas, semi-natural areas, and oil palm plantations	(2) Firms invest in palm oil production using credit from banks	(1) E → S: Palm oil production (4) E ← S: Degraded land restoration and protection for high-biodiversity governmental program	1: None	Simulated several scenarios to evaluate impacts from palm oil production to carbon emission and biodiversity loss. Produced quantified recommendation that would support decision-making process.
Catarino, R., Therond, O., Berthomier, J., Miara, M., Mérot, E., Misslin, R., Vanhove, P., Villerd, J., and Angevin, F.	2021	10.1016/j.agsy.2021.103066	Fostering local crop-livestock integration via legume exchanges using an innovative integrated assessment and modelling approach based on the MAELIA platform	1: High	2: Regional	(2) Soil water dynamics affected by spatial and weather variability	(2) Farmer management strategies to maximize yield	(1) E → S: Agricultural and livestock production (3 and 4) E ← S: Farmers applied fertilizer and insecticide to increase yield, which could pollute surface water	4: Model development and use	Simulated several scenarios to assess the sustainability performance of the integration of agriculture and livestock production. Produced quantified recommendation that would support decision-making process.
Gonzalez-Redin, J., Gordon, I.J., Hill, R., Polhill, J.G., and Dawson, T.P.	2019	10.1016/j.jenvman.2018.10.079	Exploring sustainable land use in forested tropical social–ecological systems: A case-study in the Wet Tropics	1: High	2: Regional	(1) Biodiversity and carbon sequestration in natural (protected) and semi-natural areas	(3) Government strategies in expanding protected area, increasing agricultural production, or developing wildlife-friendly farming practice	(4) Land use change based on suitability as protected, semi-natural, or agricultural area	2: Model development	Simulated three scenarios evaluating impacts of land use change on biodiversity, carbon sequestration, and agricultural production potential. Provided quantified policy recommendations to support policy-making process.
Chion, C., Cantin, G., Dionne, S., Dubeau, B., Lamontagne, P., Landry, J.-A., Marceau, D., Martins, C.C.A., Ménard, N., Michaud, R., Parrott, L., and Turgeon, S.	2013	10.1016/j.marpol.2012.05.031	Spatiotemporal modelling for policy analysis: Application to sustainable management of whale-watching activities	1: High	2: Regional	(1) Whale abundance and diversity, with movement affected by tides and water visibility	(2) Tourist satisfaction becomes the main motive for captains to move their boats	(3) E ← S: Nature tourism (4) E ← S: Manager regulations for whale conservation	2: Model development	Simulated two distinct management regimes for conserving whale population and enhancing visitor experience. Provided policy recommendations and a user-friendly interface for stakeholders and decision-makers to interact with the model

Table A1. *Cont.*

Author	Year	DOI	Title	Geographical Characteristics		SES Components Being Modeled			Stakeholder Involvement	Practical Application
				Location	Spatial Scale	Ecological Subsystem	Social Subsystem	Interactions		
ABM										
Van Schmidt, N.D., Kovach, T., Kilpatrick, A.M., Oviedo, J.L., Huntsinger, L., Hruska, T., Miller, N.L., and Beissinger, S.R.	2019	10.1002/ecy.2711	Integrating social and ecological data to model metapopulation dynamics in coupled human and natural systems	1: High	2: Regional	(1) Black rail and Virginia rail metapopulation dynamics in wetland ecosystem affected by west Nile virus and drought (2) Precipitation affected water dynamics in wetland ecosystem	(2) Landowner preference in obtaining incentive from wetland protection or selling their property (3) Government strategies in managing irrigation system	(3 and 4) E ← S: water usage and land use change in wetland ecosystem affected Black rail and Virgina rail metapopulations	2: Model development	Simulated several scenarios to assess the influence of incentive programs and west Nile virus on rail metapopulation dynamics. Did not provide policy recommendations but information on how a wetland ecosystem would respond to human actions.
SD										
You, S., Kim, M., Lee, J., and Chon, J	2018	10.1016/ j.envpol.2018.06.082	Coastal landscape planning for improving the value of ecosystem services in coastal areas: Using system dynamics model	1: High	1: Local	(1) Ecosystem composition dynamics—forest, grassland, and sand dune	(3) Government capacity in allocating budget for different program (afforestation, sand dune restoration, tourism infrastructure development)	(1) E → S: Ecosystem composition provide ecosystem service value (4) E ← S: Land use change as resulting from development of tourism infrastructure reduced forest area and negatively affected sand dune area.	1: None	Simulated landscape planning scenarios to improve long-term ecosystem service value. Produced quantified recommendation that would support policy-making process.
Chapman, A.	2016	10.1016/ j.scitotenv.2016.02.162	Evaluating sustainable adaptation strategies for vulnerable mega-deltas using system dynamics modelling: Rice agriculture in the Mekong Delta's An Giang Province, Vietnam	3: Lower middle	2: Regional	(4 and 5) Nutrient availability in sediment affected by fluvial flood	(2) Farmer technical capacity and income level to support agricultural intensification	(1) E → S: Agricultural production depends on nutrient availability in sediment (3) E ← S: Farmers use fertilizers to enrich nutrients in sediment	2: Model development	Analyzed different adaptation policies in response to annual flood and provided quantitative recommendation to support policy-making process

Table A1. *Cont.*

Author	Year	DOI	Title	Geographical Characteristics		SES Components Being Modeled			Stakeholder Involvement	Practical Application
				Location	Spatial Scale	Ecological Subsystem	Social Subsystem	Interactions		
SD										
Kopainsky, B.	2015	10.1002/sres.2334	Food Provision and Environmental Goals in the Swiss Agri-Food System: System Dynamics and the Social-ecological Systems Framework	1: High	3: National	(4) Nutrient availability in soil with carrying capacity	(1) Human demand for plant and animal products	(1) E → S: Agricultural and livestock production depends on soil nutrient availability (3) E ← S: Waste from agriculture and livestock could be utilized as fertilizers to enrich soil nutrients	1: None	Simulated several policies to increase agricultural and livestock production using non-renewable and renewable fertilizer. Provided quantitative recommendation to support policy-making process.
Piao, H., Duan, H., and Zhu, M.	2019	10.1088/1755-1315/384/1/012002	System Dynamics Simulation of Environmental Resources in Yinchuan Plain	2: Upper middle	2: Regional	(4) SO_2 content in the air as an indicator of air quality	(1 and 2) City population size and industrial activities	(2) E → S: High air concentration of SO_2 could create pathogen affecting the natural growth rate of the population (4) E ← S: Pollution from industrial activities increase SO_2 air content. As mitigation, environment protection activities are conducted using income from industrial activities	1: None	Simulated several scenarios of industrial development to study the impacts on environmental and population health. Did not produce a policy recommendation, but stimulated a discussion around certain options (scenarios).
Pouso, S.	2019	10.1016/j.ecss.2018.11.026	The capacity of estuary restoration to enhance ecosystem services: System dynamics modelling to simulate recreational fishing benefits	1: High	1: Local	(1 and 4) Fish abundance and richness with nutrient availability as its driving factor.	(2) Recreational fishing with fisherman satisfaction as output	(1)] E → S: Fish abundance and richness are the main drivers of fisher satisfaction	1: None	Simulated future scenarios of environmental changes and management decisions. Did not produce a policy recommendation, but stimulated discussion around certain options (scenarios).

Table A1. *Cont.*

Author	Year	DOI	Title	Geographical Characteristics		SES Components Being Modeled			Stakeholder Involvement	Practical Application
				Location	Spatial Scale	Ecological Subsystem	Social Subsystem	Interactions		
SD										
Tenza, A.	2018	10.1007/ s11625-018-0646-2	Sustainability of small-scale social–ecological systems in arid environments: trade-off and synergies of global and regional changes	2: Upper middle	1: Local	(2) Precipitation as exogenous driver of productivity in rangeland and irrigated land	(1) Local population dynamics pf labor in livestock and agricultural activities	(1) E → S: Agriculture and livestock production value affected by precipitation as drought indicator (5) E ↔ S: Increase in total production value and demand of labor will reduce the migration of local population. In contrast, a decrease in population size will affect abandonment of irrigated land and ranches, resulting in decreased total production value.	2: Model development	Simulated the effect of endogenous and external drivers in controlling the sustainability of the SES. Did not provide policy recommendation, but stimulated discussion on how endogenous drivers have stronger effects than external ones.
Baur, I.	2015	10.1016/ j.ecolecon.2015.09.019	Modeling and assessing scenarios of common property pastures management in Switzerland	1: High	2: Regional	(1) Common property pasture (CPP) produces fodder for livestock	(2) Farmers and corporations attempt to maximize income from stocking in CPP	(1) E → S: Livestock production depends on fodder from CPP (4) E ← S: Land use change in response to fodder requirement	1: None	Simulated four scenarios on the utilization and maintenance of CPP. Did not provide a precise forecast of future development and did not reveal any optimal solution, only provided a tool to assess the capacity of the SES to address external change.

Table A1. *Cont.*

Author	Year	DOI	Title	Geographical Characteristics		SES Components Being Modeled			Stakeholder Involvement	Practical Application
				Location	Spatial Scale	Ecological Subsystem	Social Subsystem	Interactions		
SD										
Duer-Balkind, M.	2013	10.5751/es-05751-180450	Resilience, Social–Ecological Rules, and Environmental Variability in a Two-Species Artisanal Fishery	2: Upper middle	1: Local	(1) Ecosystem consisting of two species of pen shells with their growth dynamics from immature to mature	(2) Harvesting of immature and mature animals from two pen shell species	(5) E ↔ S: Harvest affects population growth by reducing number of immature and mature populations. Meanwhile, population composition, based on the relative abundance of Pr species, has a delayed influence on the harvest rate.	1: None	Forecast the results of several scenarios (rules). Showed the importance of different management strategies on maintaining fisheries in the long term, with more fishers and larger harvests. Produced quantified recommendation that would support policy-making process.
Allington, G.R.H., Li, W., and Brown, D.G.	2017	10.1016/j.envsci.2016.11.005	Urbanization and environmental policy effects on the future availability of grazing resources on the Mongolian Plateau: Modeling socio-environmental system dynamics	3: Lower middle	2: Regional	(1) Grassland with climate controlling the grass biomass	(1) Rural and urban population as source of labor for agricultural and livestock activities	(1) E → S: Agricultural and livestock production depend on grassland net primary productivity (4) E ← S: Land use change with population size as its driving factor, i.e., the growth of urban population drives the conversion of grassland to settlements and other developed areas, and the growth of rural population drives the conversion of grassland to cropland; increasing grazing intensity could lead to desertification of grassland	3: Model use	Simulated three scenarios to predict the future resilience of grasslands in the region. Did not produce a policy recommendation, but filled knowledge gap on the role of urbanization in shaping the future of grassland health.

Table A1. *Cont.*

Author	Year	DOI	Title	Geographical Characteristics		SES Components Being Modeled			Stakeholder Involvement	Practical Application
				Location	Spatial Scale	Ecological Subsystem	Social Subsystem	Interactions		
SD										
Berrio-Giraldo, L., Villegas-Palacio, C., and Arango-Aramburo, S.	2021	10.1016/j.jenvman.2021.112675	Understating complex interactions in socio-ecological systems using system dynamics: A case in the tropical Andes	2: Upper middle	2: Regional	(1 and 2) Water dynamics controlled by vegetation cover composition (forest, crop, pasture)	(1) Population dynamics as exogenous factor	(1) E → S: Agricultural and livestock production depend on water supply (4) E ← S: Land use change in the form of deforestation could lead to soil erosion. Therefore, conservation activities are conducted through a reforestation program	1: None	Simulated several scenarios of land use and cover changes to explore its impact on sustainability of basin area. Did not produce a policy recommendation but detailed information on the influence of different land cover on mountain ecosystem function.
Zamora-Maldonado, H.C., Avila-Foucat, V.S., Sánchez-Sotomayor, V.G., and Lee, R.	2021	10.1016/j.ecocom.2020.100884	Social–ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico	2: Upper middle	2: Regional	(1 and 2) Bighorn sheep population dynamics affected by precipitation	(2) Income generated from issuing hunting permits	(1) E → S: Bighorn sheep harvest quota determines number of hunting permits that could be issued	2: Model development	Simulated rainfall variability to explore its implications for management strategies. Did not produce a policy recommendation, but facilitated discussion among stakeholders about how management strategies could address the effects of drought.
Lazar, L., Rodino, S., Pop, R., Tiller, R., D'Haese, N., Viaene, P., and De Kok, J.-L.	2022	10.3390/w14213484	Sustainable Development Scenarios in the Danube Delta—A Pilot Methodology for Decision Makers	1: High	2: Regional	(2) Precipitation and evaporation affect river flow	(1 and 3) Population dynamics and government policy to improve quality of life	(1) E → S: Aquacultural and agricultural production (4) E ← S: impact of aquaculture, agriculture, and tourism on water quality	3: Model use	Simulated four development scenarios that involved stakeholders. Produced quantified policy recommendation to support decision-making process

Table A1. *Cont.*

Author	Year	DOI	Title	Geographical Characteristics		SES Components Being Modeled			Stakeholder Involvement	Practical Application
				Location	Spatial Scale	Ecological Subsystem	Social Subsystem	Interactions		
SD										
Vermeulen-Miltz, E.	2023	10.1016/j.envsoft.2022.105601	A system dynamics model to support marine spatial planning in Algoa Bay, South Africa	2: Upper middle	2: Regional	(1) Fish biomass dynamics affected by marine health	(2) Marine wealth development consisting of several activities, e.g., fishing, shipping, tourism, and mariculture	(1) E → S: Marine health influences fishing, mariculture, and tourism and the relayed income growth (4) E ← S: Human activities (fishing, mariculture, shipping, and tourism) create pollution that deteriorates marine health	4: Model development and use	Quantitatively simulated policy and management intervention. Provided a user-friendly interface for stakeholders and decision-makers to engage with the model.
Mallick, U.B.	2021	10.3390/systems9030056	Transforming a Liability into an Asset: A System Dynamics Model for Free-Ranging Dog Population Management	3: Lower middle	3: National	(1) Free-ranging dog (FRD) population dynamics	(3) Government budget allocation for FRD management program	(4) E ← S: Government program to control FDR population through sterilization, euthanasia, and social integration (training FDR as pets or service animals [medical and military])	3: Model use	Simulations were conducted to explore effectiveness of government programs. Provided policy recommendations and a user-friendly interface for stakeholders and decision-makers to interact with the model.
Jin, L.	2022	10.1016/j.jenvman.2022.115788	Modeling the resilient supply of ecosystem function for climate change adaptive management in Wetland City	1: High	1: Local	(1 and 5) Willow population dynamics could control water level to avoid flood	(2) Development of water storage system to control water level	(1) E → S: Willow population control water level through absorption. However, uncontrolled growth of willow would occupy water storage space, resulting in a rapid rise in water level (4) E ← S: Thinning is conducted when the water storage space decreases to maintain willow vegetation ratio	2: Model development	Simulated the effect of climate change on water level for proposing adaptive management plan. Produced quantified recommendation that would support policy-making process.

Table A1. *Cont.*

Author	Year	DOI	Title	Geographical Characteristics		SES Components Being Modeled			Stakeholder Involvement	Practical Application
				Location	Spatial Scale	Ecological Subsystem	Social Subsystem	Interactions		
SD										
Song, K.	2018	10.1016/ j.envpol.2018.07.057	Simulation modeling for a resilience improvement plan for natural disasters in a coastal area	1: High	1: Local	(2 and 5) Precipitation could lead to floods	(2) Development of green infrastructure (green roof, infiltration storage facility, and porous pavement) to reduce flooding area	(4) E ← S: Construction of green infrastructure could reduce flooding in coastal area and increase resilience	1: None	Simulated the construction of three types of green infrastructure to improve flooding resilience. Produced quantified recommendation that would support policy-making process.
Hybrid										
Martin, R., and Schlüter, M	2015	10.3389/ fenvs.2015.00066	Combining system dynamics and agent-based modeling to analyze social–ecological interactions—an example from modeling restoration of a shallow lake	2: Upper middle	1: Local	(1) Population dynamics of two fish species with their prey–predator relationship (4) Nutrient availability determined macrophyte abundance	(2) House owner willingness to upgrade on-site sewage system to reduce pollutant flow into the lake	(2) E → S: High concentration of nutrients increase lake turbidity, forcing house owners to upgrade sewage system (4) E ← S: Pollution by household sewage could decrease fish population in lake	4: Model development and use	Simulated lake restoration scenarios to increase house owner willingness to upgrade their sewage system. Provided policy recommendations and a user-friendly interface for stakeholders and decision-makers to interact with the model.
Zhou, X.-Y.	2019	10.1016/ j.envpol.2019.05.020	Spatial explicit management for the water sustainability of coupled human and natural systems	1: High	2: Regional	(2) Water flow dynamics	(1 and 2) Human population dynamics with economic (agriculture and industry) activities	(4) E ← S: Human activities could drive land use change and produce pollutants that deteriorate water quality	1: None	Simulated several scenarios of water treatment to improve water quality. Provided quantified policy recommendation to support policy-making process

Note: Ecological subsystems consist of five dimensions: (1) organic carbon dynamics; (2) water dynamics; (3) Surface energy balance; (4) nutrient cycling; (5) disturbance regime. Social subsystems consist of three dimensions: (1) human population dynamics; (2) well-being and development (3) governance. Interactions consist of five dimensions: (1) ecosystem service supply; (2) ecosystem disservice supply; (3) ecosystem service demand; (4) human action on the environment; (5) social–ecological coupling.

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