







REVIEW ARTICLE

Social-ecological systems approach for adaptation to climate change

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Abstract

Adaptation to climate change has become part of national development programs (e.g., National Adaptation Planning). Though communities are adapting to climate change across the world, this perspective argues that understanding social and ecological systems requires greater attention to enhance resilience for achieving and moving beyond the Sustainable Development Goals (SDGs) in response to climate change across the world. In addition, based on a systematic literature review, this perspective identifies key research gaps and addresses relevant key challenges and future research direction for social and ecological systems (SES) adaptation to climate change. Ultimately, this may also help move from the existing limits to adaptation (intolerable risks through adaptive actions) concept to social-ecological limits to adaptation and offers an opportunity to integrate adaptation to climate change in development planning by considering both SES.

KEYWORDS

adaptation, limits, resilience, social and ecological systems (SES), sustainable development

1 | BACKGROUND

Adaptation and mitigation strategies are equally crucial for reducing the adverse impacts of climate change. However, the uncertainties in sharing the climate responsibility and climate negotiations in the post-2015 Paris Climate Agreement (PCA) (Robinson & Shine, 2018) have resulted in a much greater emphasis on adaptation to climate change (Lea Berrang-Ford et al., 2019; Dow et al., 2013) to foster sustainable development through enhancing social-ecological resilience across different scales (IPCC, 2022).

In general, adaptation refers to adjustment, moderation, or changes to social and ecological systems (SES) to avoid or recover from the effects of climate change or exploit beneficial opportunities from the process of adaptation (IPCC, 2022). Adaptation to climate change has been part of national development programs

(e.g., National Adaptation Planning (NAP)) thanks to global initiatives such as the Intergovernmental Panel on Climate Change (IPCC) reports and the United Nations Framework Convention on Climate Change (UNFCCC) activities. Though communities are adapting to climate change across the world, meeting the PCA goals and achieving the Sustainable Development Goals (SDGs) are highly challenging in some developing countries (e.g., Sub-Saharan African, and South Asian countries), where severe climate change impacts combine with other sustainability challenges, such as food security, land degradation, and economic growth, along with high emissions from agriculture and other land uses and changes in land use (IPCC, 2014a; Nhamo, 2016). In addition, despite initiatives at global, national, and local levels, climate change impacts are likely to increase over the course of the century (IPCC, 2014b). Thus, the effective integration of climate change adaptation into development planning is increasingly

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being recognized in science and policy across the globe, since this can foster sustainable development through enhancing social-ecological resilience and ensuring social and economic development while maintaining ecosystem services across different scales (IPCC, 2022).

This perspective argues that the SES approach is required for adaptation to climate change. The SES approach offers a promising opportunity to integrate adaptation to climate change effectively in development planning by considering integrated SES and continuously changing dynamics (e.g., delays, feedback, and non-linearity) of SES. This allows for both reducing the adverse impacts of climate change and increasing SES resilience to climate change in society. Although the concept of limits to adaptation (intolerable risks through adaptive actions) is increasingly informing science and policy, scientific discourses mainly focus on actors, biophysical limits, system needs (IPCC, 2022) and political consensus (Knutti et al., 2015) without considering social limits (Adger et al., 2008) and interactive dynamics (e.g., delays, feedback, and non-linearity) of SES. Therefore, the SES approach may also help move from the existing limits to the adaptation concept to social-ecological limits to adaptation. Ultimately, this SES limits to adaptation concept; (1) acknowledges biophysical, social, and economic factors of adaptation to climate change in the wider context of SES sustainability and the capacity (Dow et al., 2013) of social and ecological systems to adapt; (2) helps to strengthen SES resilience (Berkes & Folke, 1998; Biggs et al., 2012) thinking by highlighting the changing relationships of SESs and adaptation strategies required for restoring the essence and integrity of SES and mitigating hardships of unavoidable risk of climate change and; (3) offers conceptual framing for identifying SES limits to adaptation by informing debates over changes in SES and limits to adaptation in the context of wider of climate change and sustainable development. In the first section, we explain why we need the SES approach and how it may help adaptation to climate change. Next, based on a systematic review, we point out the key gaps in using SES in adaptation research. Finally, we address relevant key challenges and future research directions for SES adaptation to climate change.

2 | SOCIAL-ECOLOGICAL SYSTEMS APPROACH FOR ADAPTATION TO CLIMATE CHANGE

The SES approach combines changing social (e.g., actors, poverty) and ecological (e.g., land use, water) conditions (Berkes & Folke, 1998; Hossain, Ramirez, Szabo, et al., 2020). In general, it moves beyond the traditional approach of focusing on a discrete or individual system by recognizing ecological and social systems as complex and integrated structures that interact with each other and are shaped by continuously evolving complex dynamics (e.g., delays, feedbacks, and non-linearity) across time and scale (Berkes & Folke, 1998; Biggs et al., 2012; IPCC, 2014b; IPCC, 2022). In general, causality, feedback, non-linearity, cross-scale dynamics, and delays are key SES attributes that continuously interact and evolve between SES over time and scales (Preiser et al., 2018). The global discourses on SES theories are in

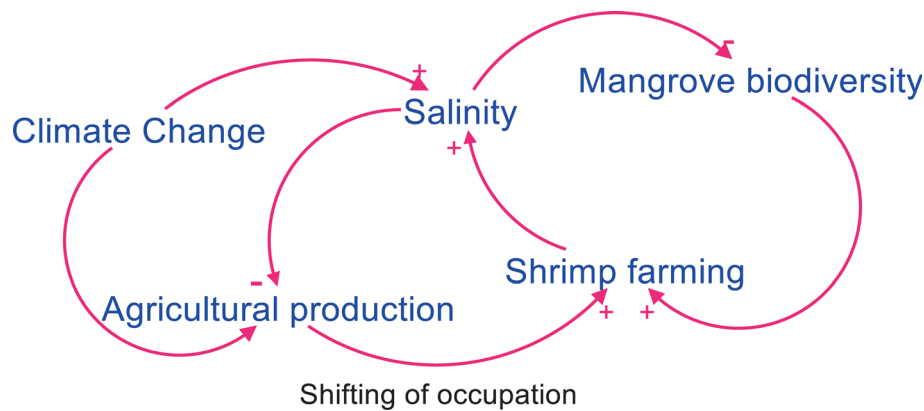
consensus that understanding SES and managing feedbacks, non-linearity, and delay are the key principles for enhancing the short- and long-term resilience of SES as complex adaptive systems (Biggs et al., 2012).

From an SES perspective, climate change is a cross-cutting and complex iterative process (Butler et al., 2016; IPCC, 2014a, 2014b; IPCC, 2022) that demands a rethinking of the way we manage and govern SES (Baird et al., 2014; Eriksen et al., 2021; Yang et al., 2022). In particular, adaptation to climate change requires an understanding of complex SES in which dynamics arise from the interactions and feedbacks between social and ecological systems (Amin et al., 2023; Folke, 2006; Hossain, Ramirez, Szabo, et al., 2020). Building on our own and others' previous work, Figure 1 provides a simplified depiction of the way adaptation to climate change is influenced by SES dynamics.

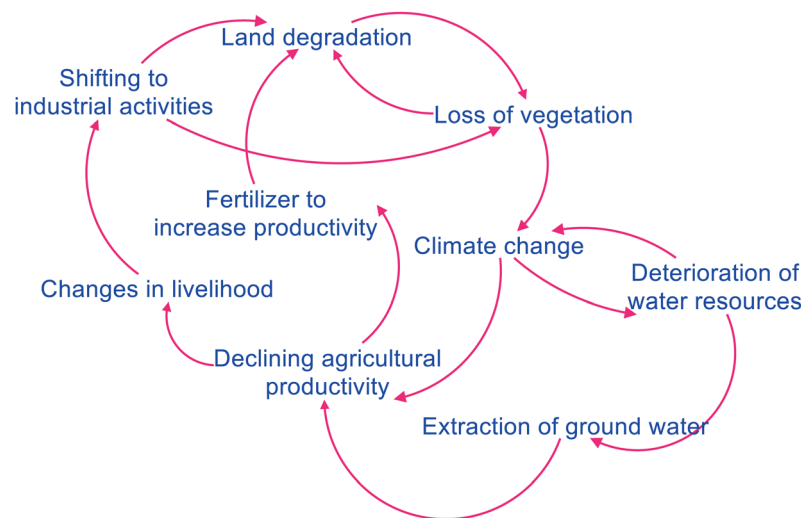
Figure 1a shows that due to the negative impacts of climate change on agricultural production through increased salinity intrusion, shifting to shrimp cultivation is seen as one adaptation option in Asian deltas. However, shrimp cultivation increases salinity in deltas and reduces mangrove biodiversity, which ultimately increases salinity further (in the absence of mangrove which maintains the balance between freshwater and seawater), which in turn increases the suitability of shrimp production in deltas. This self-perpetuating feedback loop adds an extra layer of complexity to long-term adaptation planning, as shrimp yield decreases once it reaches a certain threshold for salinity (Hossain, Ramirez, Haisch, et al., 2020; Hossain, Ramirez, Szabo, et al., 2020).

As another example, land degradation decreases vegetation (Figure 2b), which negatively influences (e.g., through releasing CO₂) climate change, in turn leading to a decrease in agricultural productivity. This reduction leads to a shift in livelihoods, which increases industrial activities and unemployment in the agricultural sector and ultimately increases land degradation due to the changes in land use (e.g., vegetation) induced by industrial activities. In addition, the deterioration in the status of water resources due to the warming climate (Rockström et al., 2009) interacts with the local climate, leading to a higher sensitivity to rising temperatures (Adel, 2002; Hossain et al., 2015). The social system, through various actors (e.g., differentiated by gender, age, and class), can respond to this degradation by extracting more groundwater and using more fertilizer for agricultural purposes, leading to self-perpetuating feedback loops that add an extra layer of complexity to adaptation planning.

In Figure 2c, social determinants of climate change responses were explored as complex non-linear causal relationships and feedback loops. Socio-demographic characteristics, such as occupation and technological diversity (e.g., types of fishing gear) usually negatively influence the available wealth (e.g., fisheries) in communities vulnerable to climate change. However, access to credit through financial organizations and personal means increases their power, which influences decision-making and leads to taking adaptive action to protect their wealth. This creates reinforcing feedback on the system through climate change adaptation. Socio-demographic characteristics (e.g., beliefs or behaviors) lead to the formation of the social



(a) Feedback loop diagram for the climate change impacts on agriculture, shrimp, and mangrove forest



(b) Feedback loop diagram for the climate change impacts on water resources, land, and agriculture.

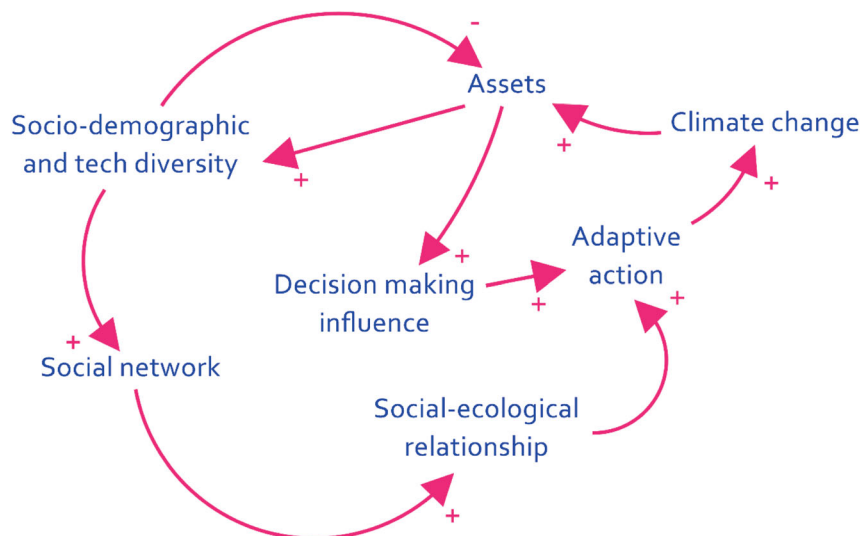
FIGURE 1 (a) Feedback loop diagram for the climate change impacts on agriculture, shrimp, and mangrove forest. (b) Feedback loop diagram for the climate change impacts on water resources, land, and agriculture. (c) Complex non-linear causal relationships and feedback loops exploring social determinants of climate change responses (Conceptualized from Barnes et al., 2020). (d) Feedback loop diagram for the impact of urban sprawling on the adaptation of social-ecological systems to climate change. Source: Conceptualized from Radwan et al., 2019; Abd-Elmabod et al., 2019; Kalantari et al., 2019; Ersoy Mirici, 2022; Zawadzka et al., 2021.

network. People's participation in the social network ensures a sustained understanding of the social-ecological relationships through the experience sharing from the long-term practitioners and leads to adaptive action through understanding the systems of the community for sustainable climate change adaptation and resource protection.

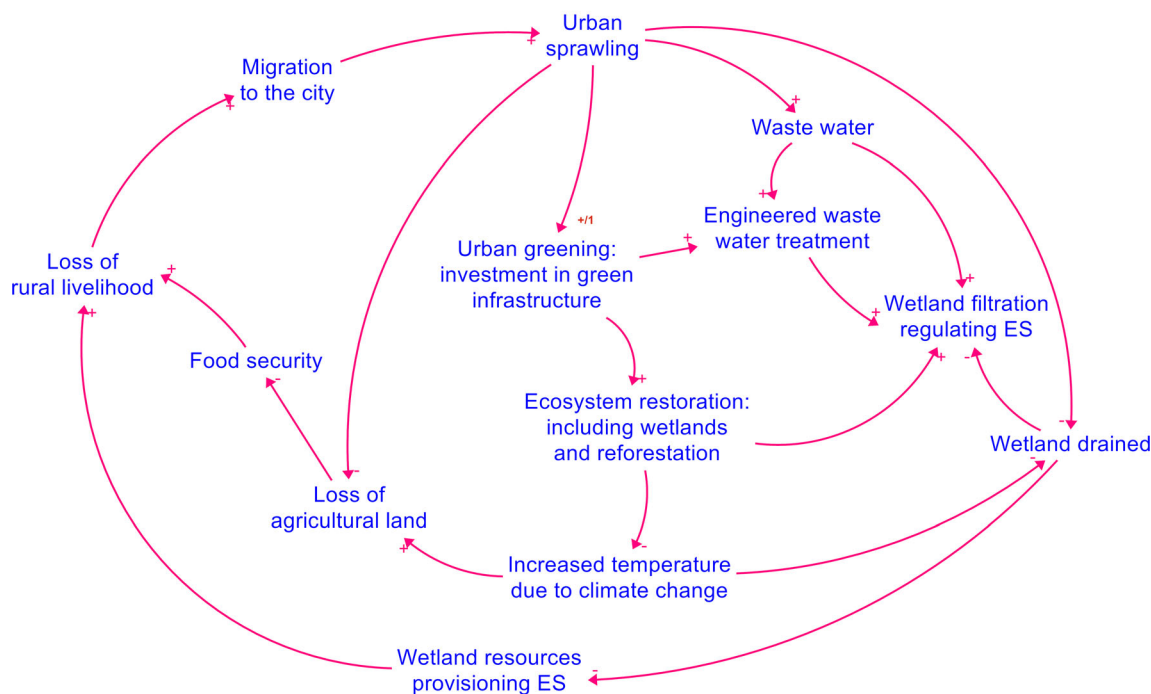
Urban sprawling (Figure 1d) is the dynamic extension of urban areas toward rural spaces. We show the importance of integrating the SES approach to analyze the impact of climate change in the context of urbanization. The urban extension involves the loss of agricultural land and threatens food security, degrades natural resources, ecosystems, and the services they provide to human societies, for example, through land use and water changes and feedback in many regions around the world, such as in the Nile Delta (Abd-Elmabod et al., 2019; Kalantari et al., 2019; Radwan et al., 2019). With the loss of wetland

ecosystem services, urban and rural SES becomes more vulnerable to climate change. Moreover, the loss of rural livelihood increases migration to the city, which increases urban sprawling. Policies involving investments in green infrastructure (Ersoy Mirici, 2022) based on combined natural and engineered wastewater treatment can support the restoration of ecosystems (wetlands and forests) to benefit from wetlands regulating ecosystem services, which can mitigate the effects of climate change in both rural and urban areas (Zawadzka et al., 2021).

Self-perpetuating feedback loops and interactions in SES often lead to nonlinear changes or regime shifts if certain thresholds are crossed. For example, agricultural (both maize and rice) production declines drastically when a specific temperature threshold is crossed and when rainfall declines during certain periods of crop growth



(c) Complex non-linear causal relationships and feedback loops exploring social determinants of climate change responses (Conceptualized from Bernes et al., 2020).



(d) Feedback loop diagram for the impact of urban sprawling on the adaptation of social-ecological systems to climate change. Sources: Conceptualized from Radwan et al., 2019; Abd-Elmabod, 2019; Kalantari et al., 2019; Mersoy Mirici, 2022; Zawadska et al., 2019.

FIGURE 1 (Continued)

(Hossain, Ramirez, Haisch, et al., 2020). In addition to the interactions and feedbacks in SES, there is often a delay between the point of crossing the threshold temperature and the drop in maize production. This “time-lag effect” adds further complexity to SES dynamics.

Such dynamics challenge decision-makers, who need to consider new priorities and dynamic changes over time (short and long-term) (Jurgilevich et al., 2017). In overcoming these challenges, integrating

complex SES dynamics (interaction, feedbacks and non-linearity) into climate change adaptation modeling (conceptualized in Figure 1a-d) is required to explore adaptation pathways (describing temporal sequences of adaptation) and develop robust adaptive plans. Therefore, adaptation planning without consideration of SES dynamics could lead to erroneous conclusions being drawn and limit the long-term benefits of adaptation to climate change.

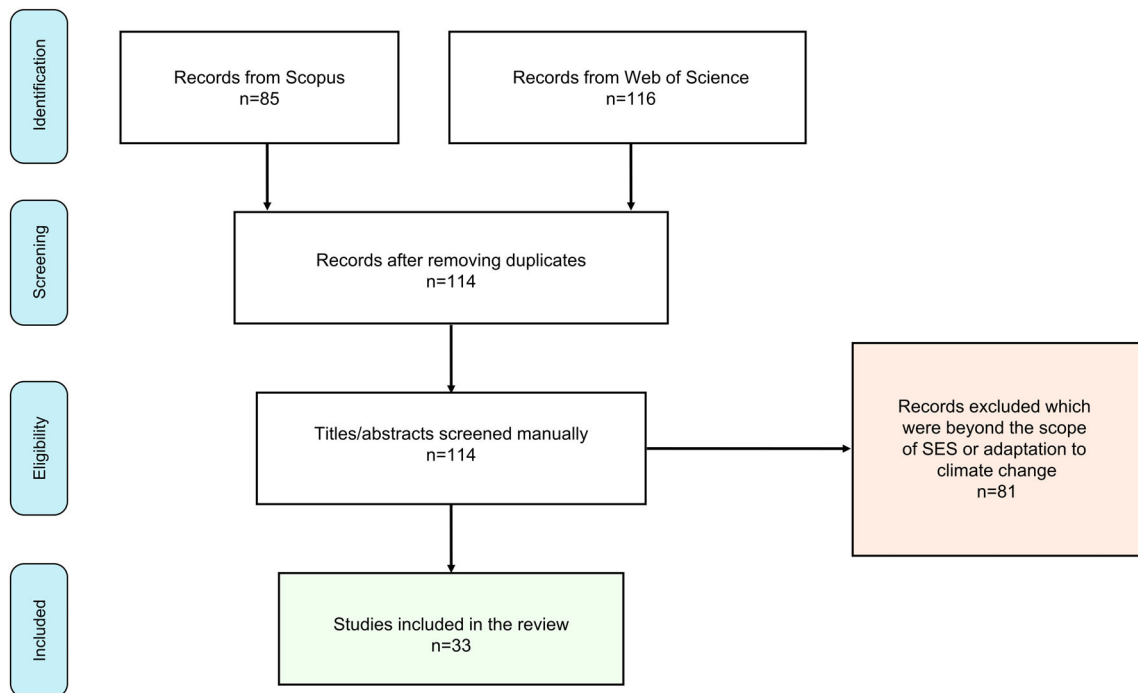


FIGURE 2 Overview of publications on climate change adaptation and social-ecological systems approach from Web of Science and Scopus.

The SES approach can help with the effective integration of climate change impacts and responses in development planning (Hossain & Alamgir Kabir, 2017), which can foster sustainable development through enhancing social-ecological resilience (Park 2023) and ensuring social and economic development while maintaining ecosystem services across different scales (IPCC, 2014b). SES dynamic perspectives can support progress toward sustainable development through (1) avoiding narrow assumptions about “natural” systems in order to enhance resilience to climate change (Huntsinger & Oviedo, 2014); (2) generating knowledge about the social-ecological conditions, drivers, trends, interrelations, and feedbacks among variables (Dearing et al., 2015); (3) determining and explaining actors' visions and political desires as well as the need for adaptation responses as part of the target knowledge (Maani, 2013; Pohl et al., 2010); and (4) identifying synergies and trade-offs when shifting existing practices toward adaptation to climate change (Maani, 2013).

3 | METHODS

A three-step process was followed to answer our research question “To what extent has adaptation to climate change research focused on the SES approach?”. In addition to providing insights into the use of the SES approach in climate change adaptation research, we identified the gaps, key challenges, and future research direction for CCA based on a systematic review and our previous experience working on SES and adaptation to climate change. Box 1 defines the key terminologies used in this perspective.

BOX 1 Definition of key terminologies.

Social and ecological systems (SES): Ecological and social systems as a complex and integrated systems that interact with each other and are shaped by continuously changing dynamics (e.g., delays, feedback, and non-linearity) across time and scale.

Causality: Theorizes cause–effect relationships, which refer to changes in the variable, is the reason for the changes in the value of another variable.

Feedback: Constitutes a reciprocal relationship (outputs routed back as inputs) that creates either positive or negative feedback loops.

Resilience: Capacity to absorb, adapt or transform in the face of continuously changing dynamics (including sudden or abrupt changes) in social-ecological systems.

Dynamic vulnerability: Accounts dynamic relationships (interactions, feedback, and nonlinearity) among social and ecological indicators of vulnerability across time and scale.

Social-ecological (SES) limits to adaptation: Consideration of both social and ecological limits, which may evolve due to dynamic relationships (e.g., feedback) between SES components. This SES limit is the point at which an actor's objectives or SES needs or adaptations cannot be secured from intolerable risks of climate change.

Figure 2 represents the literature search and selection process for the review. In the first step, the literature search was limited to peer-reviewed articles published in English using Web of Science and Scopus with the following search terms: (climate*) AND (adapt* OR Cop* OR resilience*) AND (causality OR feedback* OR “non-linearity” OR “time-lag” OR “delay” OR “cross-scale dynamic”) AND (“social-ecological” OR “socio-ecological” OR “social and ecological” OR “human-nature*” OR “human and nature*” OR “human-environment*” OR

SES). Second, a total of 140 papers were included in the initial screening after removing the duplicates from Scopus ($n = 85$) and Web of Science ($n = 116$). In the third step, all remaining articles were screened manually by examining the article titles, keywords, abstracts and text, leaving a total of 33 papers. The rest of the articles were beyond the scope (SES, adaptation to climate change) of the research topics. All articles were cross-checked by several reviewers before excluding papers to reduce possible bias.

4 | REVIEW RESULTS: SOCIAL-ECOLOGICAL SYSTEMS APPROACH IN ADAPTATION RESEARCH

We have organized the results based on the multiple lessons (e.g., sectors, variables, methods, and addressing SES attributes) from our systematic review in terms of how the SES approach has been used for adaptation to climate change. SES are complex adaptive systems characterized by feedbacks, non-linearity, emergence, path dependence, and thresholds that interact across multiple spatial and temporal scales (Berkes & Jolly, 2002). Figures 3 and 4 simplify the findings of the systematic review in an illustrative manner, showing how SES approaches are applied in adaptations to climate change research.

Our systematic review (Figure 3) primarily focused on 33 articles examining SES and adaptation to climate change across the world. In general, over the period 2002–2020, adaptation to climate change research focusing on SES has mainly been limited to the sectors of fisheries, forestry (forest fire), invasive species, and tourism. Much of the research on adaptation to climate change and SES was initiated

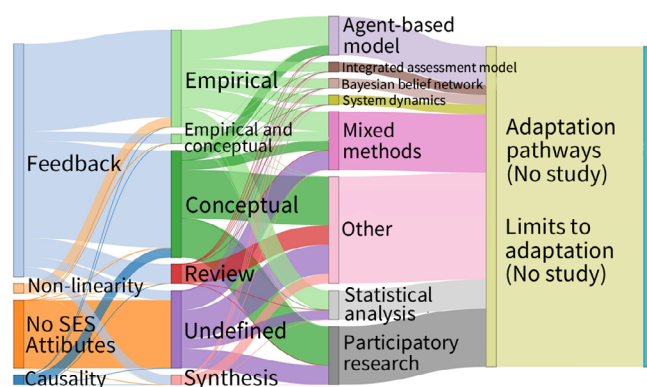


FIGURE 3 Five major themes (SES attributes, types of studies, types of analysis, adaptation pathways, limits to adaptation) in the systematic review focusing social-ecological systems (SES) and adaptation to climate change. The width or thickness of the linkages corresponds to the frequency (e.g., thicker lines indicating stronger connections, a single line “no connection”) of connections between themes. The feedback focus, which was the most elicited, shares an equal maximum reference with both empirical and conceptual studies without focusing on adaptation pathways and limits to adaptation.

at regional and local levels, with considerably fewer articles focusing on global, coastal, and delta levels.

There are multiple lessons from the systematic review focusing on SES and adaptation to climate change. First, so far, there have only been a few studies (Figures 3 and 4) that explicitly used the SES approach and aimed to understand how feedbacks and nonlinearity could influence future adaptation planning. Most of them used a qualitative approach for the conceptualization of feedbacks in SES. A study by Burke et al., (Burke et al., 2015) was the only empirical study that considered non-linearity to understand the effect of temperature on economic production. Though some of the studies used an empirical approach to understand and operationalize the SES feedbacks, most of them were limited to understanding the current state of SES; they did not identify pathways to adaptation or understand how feedbacks could influence future adaptation strategies.

Second, the majority of the research addressed social variables through income and price, fertilizer, technical capacity, market, and immigration (e.g., Chapman & Darby, 2016; Dutra et al., 2018; Li & Ford, 2019). The most addressed ecological variables were forest fire, invasive species, water quality, and supply (Soboll & Schmude, 2011; Tiller et al., 2016), and fisheries and fishing (Bayliss et al., 2018; Ojea et al., 2020). Additionally, the identification of social variables, such as net economic position, price, affordability, yield, and minimum wage level in the adaptation strategies was recognized (Chapman & Darby, 2016). Despite the relatively limited range of variables in these prior studies, it is extremely important to understand that social variables in adaptations are diverse; they include changing social (e.g., actor capacities, household behavior, social norms and institutions, values) and ecological (e.g., land use, water) conditions that are not yet considered for a complete understanding of drivers influencing limits to adaptation. Thus, such limiting drivers may constrain the chances of inclusion of other drivers that can help adapting to climate change, based on the issue of which pathways to accelerating the transformation to sustainable adaptation to climate change can be explored.

In the realm of adaptation to climate change, many local-level studies address SES attributes focused on feedback mechanisms. A study by Nettleier et al. (2017) identified “tightness of feedback” as the ability of managers to identify any disturbance or retort, whereas Li and Ford (2019) identified a combined feedback loop of agriculture and monetary economy, as well as socio-environmental and finally socio-cultural factors. They emphasized that both internal and external factors drive changes and that the responses of community members create both reinforcing and balancing feedback loops that overall generate increased stress on agricultural systems, social structures, and environmental components. A more global perspective on feedback mechanisms suggested that feedback subsystems within the earth system initially link fire regimes to atmospheric and climate dynamics, and later connect changes in fire regimes to changes in the provision of ecological services and the consequences for human systems, more commonly identified as adaptability (Lavorel et al., 2006). For instance, the authors gave fire as an example of providing feedback loop mechanisms. While the flammability of fire can be

Example	SES Attributes			Spatial Scale							Temporal Scale				Methods				
	Feedback	Causality	Non-linearity	Global	Regional	Local	Coastal	Cross scale	Delta	Riverbasin	Watershed	Current	Future	Historical	Not indicated	Conceptual	Empirical	Review	Synthesis
Urfels et al., 2021	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Ojea et al., 2020	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Lawrence et al., 2020	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Hollowed et al., 2020	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Fedele et al., 2020	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Zagaria et al., 2020	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
D'agata et al., 2020	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Barnes et al., 2020	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Silva et al., 2020	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Thanh et al., 2020	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Ciobanu and Saisele 2020	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Beeton et al., 2019	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Li and Ford 2019	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Bayliss et al., 2018	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Dutra et al., 2018	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
De stefano et al., 2017	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Nettier et al., 2017	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Chapman and Darby 2016	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Devisscher et al., 2016	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Giuliani et al., 2016	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Murphy et al., 2016	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Tiller et al., 2016	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Burke et al., 2015	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Rammer and Seidl 2015	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Shackleton and Shackleton 2012	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Adger et al., 2011	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Soboll et al., 2011	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Soboll et al., 2011	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Bunce et al., 2010	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Chapin et al., 2010	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Lavorel et al., 2007	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Chapin et al., 2006	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Berkes et al., 2002	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

FIGURE 4 Overview of publications on climate change adaptation and social-ecological systems (SES) approach from Web of Science and Scopus. Climate change adaptation studies mostly focused on feedback, with comparatively no focus on causality and non-linearity. The review identified that climate change adaptation studies are dominated by current knowledge, with comparatively little focus on historical and future perspectives of climate change adaptation and SES.

considered negative feedback if the ecosystem services threatened by the fire are of a high market value, the same situation can generate positive feedback if the market value of the lost ecosystem services is low, thereby creating land abandonment.

Though previous literature introduced the idea of linkages between social and environmental sustainability through sustainable adaptations (adaptations contribute toward social equity and environmental integrity) concept, but limited to two pillars of sustainable development, with limited understanding and conceptualization of interactions between social, economic and environmental systems. In addition, the concept is limited in the scientific discourses without operationalizing (empirical examples) the idea in real-world examples (Brown, 2011; Hritonenko & Yatsenko, 2022; Yang et al., 2020). In particular, previous studies have failed to use the SES approach explicitly to understand how feedbacks and nonlinearity could influence future adaptation planning in the context of wider aspiration for sustainable development. Studies have linked the response of the future economy to climate change (Burke et al., 2015) and identified the historical patterns of human development and the way the future economy might respond to a changing climate. Likewise, agricultural systems call for dynamic coadaptation to secure food production due to uncertain hydrological regimes as a result of climate change (Giuliani et al., 2016). Citing examples from ski areas, Soboll and Schmude (2011) presented an approach to consider within SES that could provide

an insight into the rise of tourism demand-side examinations concerning the perception of climate change and resulting behavioral shifts.

To summarize the current knowledge, only a few studies have provided empirical insights into the way SES feedbacks influence adaptation to climate change. Discussion of limits to adaptation is rare and limited, and few comprehensive studies have considered adaptation pathways utilizing SES. In addition, the changing social-ecological drivers for adaptation strategies, actors (including household behavior), and SES limits to adaptation have not been included in adaptation research. Combining these aspects would allow for the exploration of co-evolving pathways to accelerating the transformation to sustainable adaptation to climate change.

5 | MOVING FORWARD AND CHALLENGES FOR ADAPTATION FUTURES

5.1 | Future research direction in social-ecological systems approach and climate change adaptation research

Recommendations across articles embraced the inclusion of simulation models. These may provide flexible platforms to represent

complex SES dynamics and can explore the effects of diverse circumstances that might not be solely evident from qualitative analysis (Bayliss et al., 2018; Beeton et al., 2019) or can be used for testing various policy options (Ciobanu & Saysel, 2020). Also recommended were the careful examination of critical thresholds by policymakers to determine the immediate need for action (Thanh et al., 2020), or to link policy solutions with SES adaptation-transformation response (Ojea et al., 2020). There were calls for collaborative planning models that can engage the public in long-term thinking and planning that connect different domains of interest that impact climate change cascades (Lawrence et al., 2020).

Recent scientific advances in SES and adaptation to climate change reveal several issues that need to be addressed in future climate change adaptation research. In addition to discussing ongoing adaptation research, such as cross-sectional analysis of adaptation determinants, adaptation options using stakeholders' perceptions, and model-based scenario analysis, this section elaborates how SES considerations comprehensively help and complement future adaptation to climate change by making methodological suggestions. These suggestions are not exhaustive but provide an idea for future research direction and are followed by insight into the available methods. Specifically, we propose four ways in which incorporating an SES perspective into research can strengthen future adaptation to climate change.

First is understanding SES. The knowledge relating to understanding SES and the way adaptation strategies and their determinants (e.g., social, and ecological factors) are changing across SES may help understand the fundamental (e.g., drivers, trends, feedbacks) changes of SES and enable learning from SES relationships for future incremental and transformative adaptation planning.

Much work on adaptation to climate change has been limited to determinants of adaptations (e.g., Barnes et al., 2020; Kabir et al., 2021; Kandel et al., 2023), without incorporating SES or investigating how these determinants of adaptation to climate change are changing across the temporal and spatial scales of SES. The SES determinants for climate change adaptation require longitudinal analysis in order to understand the transformative response for the social systems (Dow et al., 2013) and predict the signal for the adaptation tipping point of the SES (Lenton et al., 2008).

We argue that understanding SES characteristics and dynamics is central to adaptation to climate change. It may help understand the drivers, trends, and complex relationships (interactions, feedback, non-linearity) between SES, which emphasize the inseparability of adaptation to climate change and SES.

Second, more research is needed on dynamic vulnerability. Previous studies on climate change adaptation have mostly featured vulnerability analyses considering the sensitivity, exposure, and adaptive capacity of SES. There has been an increasing effort to assess vulnerability using SES approaches given recognition of the interdependency of positive or negative outcomes (Beroya-Eitner, 2016; Hagenlocher et al., 2018; Peng et al., 2023). For example, the Global Deltas Risk Index (GDRI) uses a modular approach to social and ecosystem sub-systems, as well as susceptibility and adaptive capacity, which can be assessed first in isolation and then iteratively combined (Anderson

et al., 2021). However, dynamic vulnerability analysis is mostly limited to temporal dynamics of vulnerability, and does not account for the interactions, feedbacks, and nonlinearity among these indicators of vulnerability.

A decomposing assessment based on individual sub-systems, without considering the relationships and dynamics between SES, may be arbitrary or reduce the accuracy of actual vulnerability (Beroya-Eitner, 2016; Peng et al., 2023). Research efforts toward improving model specifications and increasing the accuracy of vulnerability assessments have also led to greater recognition of the need to consider the interacting elements of SES. The interconnections are clear between, for example, living in poverty, which is a feature of social vulnerability, and living in an area of environmental degradation, which is a feature of ecosystem vulnerability. At this nexus, relevant dynamic interactions between factors, such as food security, livelihood, health, and availability of natural resources may be important determinants of vulnerability. These interconnections occur at different spatial and temporal scales.

Third is modeling SES for adaptation planning. The modeling of SES allows adaptation planners to move beyond focusing only on climate adaptation by integrating social and ecological variables, including the way social variables, such as institutions and actors could influence adaptation strategies both in the short and long term.

Despite challenges in the ecological complexity of CCA, for which models are becoming increasingly advanced, knowledge regarding the way the social system will adapt is even more complex at different spatial and temporal scales (Berrang-Ford et al., 2015). Household-level adaptation behaviors are highly dependent on context and specific climate-related threats, but may include preparatory actions (for example, having an emergency kit or climate-proofing houses), social networks, power, seeking information about climate-related hazards or ways to adapt, and supporting climate adaptation policies.

Considering that the adaption paradox of climate change impacts is experienced at local, individual, and household levels (McNamara and Buggy 2016), and that the SDGs aim to leave no one in the world behind, a novel understanding of feedback and modeling complex dynamics in social and ecological systems is required. This would include societal behavior and behavioral adaptation dynamics in order to investigate how decisions about adaptations are made and how these behavioral adaptation dynamics may feedback to SES, which could ultimately be influenced by SES itself (Adger, 2009; Barnes et al., 2017).

Fourth, further research on social-ecological limits to adaptation is needed. In general, according to IPCC, limits to adaptation are defined as “*the point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions*” (IPCC, 2022). This perspective of definition mainly focuses on actors and system needs instead of understanding and considering the interactive relationships (e.g., feedbacks) of a system. Though adaptation has already been recognized as a dynamic feature of society instead of biophysical changes by society, the focus on actors' objectives could limit the utilization of the concept as all changes due to adaptation to climate change may not be a desire to all actors (Eriksen

et al., 2015; Eriksen et al., 2021) and the adaptations may differ according to actor's perspectives, experiences and evaluation of risk in society (Dow et al., 2013). In addition, the actor's objective could be changed and influenced (IPCC, 2014a, 2014b) due to changes over time in societal (e.g., values) and political context (e.g., changes in government, relationships, and visions among actors), which could lead to adoption, revision or abandoning the limits of adaptation.

The current scientific understanding of limits to adaptation lacks the integration of an SES approach and mainly refers to biophysical limits to adaptation, without considering social limits to adaptation (Adger et al., 2008). In addition, it has been argued that limits to adaptation (a 2°C target) are the result of a political consensus informed by science (Knutti et al., 2015). However, no scientific assessment has ever been made (Figure 3) that defines SES limits to adaptation by taking into consideration both social and ecological limits, which may evolve due to interactive relationships (e.g., feedbacks) between SES components. Figure 5, conceptualizes a schematic SES limits to adaptation to climate change with a focus on modeling complexity and adaptation complexity. The changing SES relationships (interactions, feedbacks, and nonlinearity) may lead to incremental adaptation (maintain the essence and integrity of a system) in the short terms and small scale where, SESs are connected for individual benefits and coping strategies (Wilson et al., 2020). In the long run, the changing relationships of SESs and adaptation strategies may push the SES beyond SES limits, beyond which, changes in the fundamental attributes or structure of SES are required for adaptation (transformational adaptation) to changing climate. Though such types of transformational adaptation could increase the resilience of SES, future risk of climate change, SES dynamics and incremental adaptation strategies may push SES limits further, beyond which, adaptation strategies may not be possible under extreme impacts of climate change. Though it could be highly uncertain but depending on what adaptation strategies are being practiced and climate change impacts in the long run,

SES could be restored to maintain the initial phase (from where the adaptation practices initiated) characteristics and integrity of SES. Therefore, there is an urgent need to define SES limits to adaptation so that actors can plan to mitigate hardships that cannot be avoided.

5.2 | Challenges and concluding remarks

Applying the SES approach to adaptation to climate change raises multiple challenges. The selection of a conceptual framework could pose a major challenge to integrating SES and adaptation to climate change for sustainable development. This is arguably the case with even the most widely used SES framework, introduced by Elinor Ostrom (Ostrom, 2007; Ostrom, 2009), which does not provide any suggestions for integrating SES dynamic feedbacks. In addition, existing modeling approaches are not at a sufficiently advanced stage to adequately understand and model the complex dynamics of SES. Nevertheless, modeling approaches are often complicated and not user-friendly, with a high level of uncertainty in terms of outputs and validation. As such, application of such models could be limited to decision-makers for adaptation planning (Hossain & Ifejika Speranza, 2019; Verburg et al., 2016). Similarly, to other research, the classical challenge in adaptation science is data availability. Therefore, in addition to the existing challenges of social and ecological long-term data availability, there is a knowledge gap in terms of the types and drivers of adaptations and the way these adaptations evolve or change across time and scale (Tompkins et al., 2018).

For example, long-term comparisons of social vulnerability are possible in data-rich environments like the United States (Cutter & Finch, 2008). However, such analyses rely nearly exclusively on census data and therefore do not capture a comprehensive set of SES elements or dynamics. SES approaches using system dynamics principles have the advantage of accounting for causal relations, feedback loops,

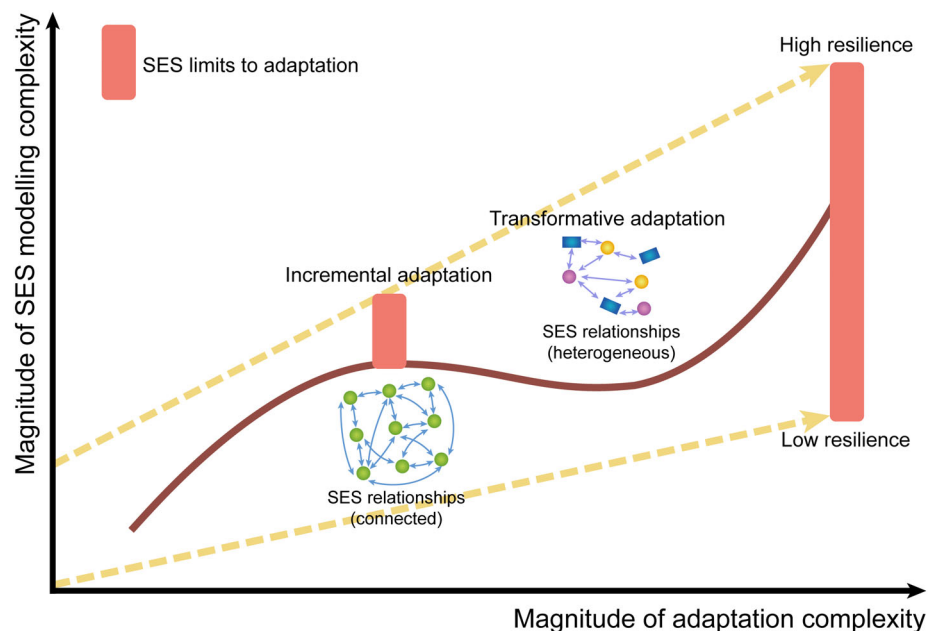


FIGURE 5 Hypothetical schematic of the social-ecological systems (SES) limits to adaptation to climate change.

and thresholds (Filatova et al., 2016), in line with the predominant theoretical understanding of vulnerability and risk established using other approaches and across various disciplines.




In using all these approaches and overcoming challenges, we could move adaptation strategies beyond the scientific approaches that lack the integration of the SES approach. In addition, we need to move beyond the conceptual approach of applying SES by operationalizing it in real-world adaptation studies in order to provide scientifically grounded information to decision-makers for exploring trade-offs and synergies across scales of adaptation pathways within the SES limits of adaptation to climate change. In addition, co-development of adaptation pathways engaging stakeholders is required, not only to account for the heterogeneity of impacts, adaptations, and SES across scales, but also to co-develop SES mental models and the future pathways within which they will strive to live.

In conclusion, previous studies (e.g., Berrang-Ford et al., 2021, Thomas et al., 2021) including IPCC reports (IPCC, 2022) acknowledged the theoretical discussion and the absence of empirical understanding of limits to adaptation research. Our review, similar to others (e.g., Thomas et al., 2021; Adger et al., 2008), shows that the limits to the adaptation concept is mainly limited to the actor's objectives, biophysical limits, the system needs and political consensus. Our perspective and framework argue that the SES approach is required for adaptation to climate change and the limits to the adaptation concept need to consider interactive and changing SES dynamics (e.g., delays, feedback, and non-linearity) over time and scale. In addition, this perspective identifies key research gaps and addresses relevant key challenges and future research direction for SES adaptation to climate change. Though the IPCC assessments have recognized SES through the lens of human-nature relationships, there have been no main chapters focused on SES dynamics or approaches for adaptation to climate change. The next cycle of IPCC assessment (AR7) should include SES dynamics for adaptation to climate change as a key chapter by engaging the expertise of those working with SES. Integrating SES into adaptation planning helps to expand the ongoing initiatives of adaptation and avoid dangerous climate change by understanding SES in the wider context of sustainable development and adaptation science, which is required for both incremental and transformative adaptations. This helps to avoid maladaptation through unintended systemic trade-offs and the point of no return, after which adaptation to climate change could become impossible.

AUTHOR CONTRIBUTIONS

Md Sarwar Hossain: Conceptualization, Methodology, Analysis-articles reviewed, Visualization, Writing-Original draft preparation. Sayantani M. Basak: Analysis-articles reviewed, Visualization, Writing (Review results)-review. Md Nurul Amin: Analysis-articles reviewed, Visualization, Writing-review. Carl C. Anderson: Analysis-articles reviewed (vulnerability), Writing (vulnerability)-review and editing. Emilie Cremin: Analysis-articles reviewed (SES and adaptation), Writing (Case study 3 on SES dynamics and adaptation)-review and editing. Fabrice G. Renaud: Writing-review and editing.

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