Characterizing Climatic Socio-Environmental Tipping Points in Coastal Communities: A Conceptual Framework for Research and Practice

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Key Points:

- The study presents a conceptual framework of climate-related tipping points in socio-environmental systems
- It identifies and describe three tipping mechanisms: feedback processes, cascading linkages, and nonlinear relationships
- An expert panel of coastal practitioners validated the framework and provided multiple examples of tipping points in practice

Abstract

The concept of climate tipping points in socio-environmental systems is increasingly being used to describe nonlinear climate change impacts and encourage social transformations in response to climate change. However, the processes that lead to these tipping points and their impacts are highly complex and deeply uncertain. This is due to numerous interacting environmental and societal system components, constant system evolution, and uncertainty in the relationships between events and their consequences. In the face of this complexity and uncertainty, this research presents a conceptual framework that describes systemic processes that could lead to tipping points socio-environmental systems, with a focus on coastal communities facing sea level rise. Within this context, we propose an organizational framework for system description that consists of elements, state variables, links, internal processes, and exogenous influences. This framework is then used to describe three mechanisms by which socio-environmental tipping could occur: feedback processes, cascading linkages, and nonlinear relationships. We presented this conceptual framework to an expert panel of coastal practitioners and found that it has potential to characterize the effects of secondary climatic impacts that are rarely the focus of coastal risk analyses. Finally, we identify salient areas for further research that can build upon the proposed conceptual framework to inform practical efforts that support climate adaptation and resilience.

Plain Language Summary

In the face of climate change, there is growing concern that incremental adaptation measures will be insufficient in addressing climate risks. Socio-environmental tipping points describe situations where a small change or pressure results in a societal system moving into a fundamentally different state. This concept is increasingly used to describe risks from climate change and the meaningful societal changes necessary to reduce these risks. However, understanding how climatic tipping points might unfold in socio-environmental systems is very challenging because these systems are highly complex, with human, built, and environmental components that interact in unpredictable ways. This research presents a framework for describing tipping points in socio-environmental systems, and uses this descriptive framework to identify three tipping point mechanisms. These are feedback processes, cascading linkages, and nonlinear relationships. A panel of coastal practitioners reviewed the framework and found that it could capture the multiple potential tipping points that they have found in their work. By developing a common way of describing climatic tipping points in socio-environmental systems, this framework can support comparative studies across different locations and the development of computational models for exploring the impact of tipping points and potential interventions.

1 Introduction

In the face of rapid and profound changes in the Earth's climate system, the concept of tipping points is becoming an increasingly widespread framing to describe climate change risks. This concept has been widely applied to describe abrupt and irreversible changes where a biophysical phenomenon moves from one state to another, such as the collapse of the Greenland ice sheet or cessation of the Atlantic Meridional Overturning Circulation ocean currents **(Lenton et al., 2019)**. More recently, the concept has been extended to the context of socio-environmental systems (SES) where humans interact with the natural and engineered components within their environments **(Elsawah et al., 2017)**. This is motivated by an interest in tipping point dynamics that could support climate mitigation and resilience **(Lenton, 2020)**. One appealing aspect of the tipping points framing is its potential to support rapid, significant changes that could accelerate the societal response to climate change **(Winkelmann et al., 2022)** and transformative adaptation **(Fedele et al., 2020)**. Socio-environmental tipping points have several elements that distinguish them from climatic or biophysical tipping points, including the role of human agency, the relevance of social-institutional network structures, different spatio-temporal scales, and a high degree of complexity **(Winkelmann et al., 2022)**.

Multiple definitions for socio-environmental tipping points exist in the literature (Table 1). Some definitions have a mathematical or quasi-mathematical focus that specifically centers on feedback dynamics **(e.g., Lenton, 2020; Lenton et al., 2022)**. These definitions focus on the process of tipping, and specifically the balance between positive and negative feedbacks that can propel a system into a new stable state defined by different feedback processes. Other definitions take a more general, intuitive approach and are based on the concept of a small event or change in a system resulting in disproportionate system-wide impacts which may be rapid or irreversible and move the system into a different stable state **(van Ginkel et al., 2020; Milkoreit et al., 2018; Tàbara et al., 2022)**. These definitions are more focused on the outcome of a tipping process, rather than the specific processes or dynamics that cause it. Definitions also exist that aim to capture both the process and outcome of tipping points, coupling both qualitative and mathematical elements **(Winkelmann et al., 2022)**. Several studies specifically define positive or intentional tipping points that could lead to rapid growth in mitigation and adaptation actions **(Lenton, 2020; Lenton et al., 2022; Tàbara et al., 2022)**,with the acknowledgment cumulative prior action is required to move the system to a state where tipping is possible **(Tàbara et al., 2022)**. A multidisciplinary review found that even though numerous tipping point definitions exist in the literature, they include many common themes with the most frequent being multiple states, abruptness, feedbacks, and limited reversibility **(Figure 1; Milkoreit et al., 2018)**. After these core themes, the next most common suggest system complexity and salience (Figure 1). While these elements of complexity and salience may not be necessarily define tipping points, they do suggest a common perception across the research community that tipping points should be focused on complex problems with societal relevance.

Source	Definition of Tipping Points
Lenton, 2020	Cases where a small perturbation causes a qualitative change in the future state or trajectory of a system. This can come about because the perturbation triggers a change in underlying system dynamics, triggering a strong self-amplifying (mathematically positive) feedback that propels the system from one stable state to a different one.
Lenton et. al, 2022	Cases where a small intervention leads to large and long-term consequences for the evolution of a complex system, profoundly altering its mode of operation. This includes the possibility of intentional **positive tipping points**.
Milkoreit et al., 2018	A **social tipping point** occurs within a social-ecological system at the point when a small quantitative change inevitably triggers a non-linear change in the social component of the social-environmental system, driven by self-reinforcing positive feedback mechanisms, that inevitably and often irreversibly lead to a qualitatively different state of the system.
Van Ginkel et al., 2020	**Climate change-induced socio-economic tipping points** are cases where a climate change induced, abrupt change shifts a socio-economic system into a new, fundamentally different state.
Tabara et al., 2022	**Positive socio-ecological tipping points** are moments when, due to previous cumulative and targeted interventions or individual activities, an additional action or event is able to shift a given social-ecological system towards a more just and sustainable development trajectory or configuration.
Winkelmann et al., 2022	**Social tipping** occurs in a social system where, under certain conditions, small changes in the system or its environment can lead to a qualitative (macroscopic) change, typically via the cascading network of effects such as complex contagion and positive feedback mechanisms.

Table 1: A sample of definitions relevant to SES tipping points.

Figure 1: Components of tipping point definitions identified in a multidisciplinary literature review (Milkoreit et al., 2018; reproduced under Creative Commons 3.0 license). These components are organized by the frequency with this they appeared across studies. The most commonly used themes (inner circle) are all related to the tipping process itself. The less frequently used themes in the middle circle relate to system complexity, while the outermost ring largely points towards a salience and relevance of tipping points.

Existing research on SES tipping points has predominantly focused on either renewable energy transitions or primary industries, such as fishing, forestry, and agriculture. Evaluations of tipping points toward growth in renewable energy largely focus on technology adoption, building upon a large body of research on socio-technical transitions **(Lenton et al., 2022)**. Within this perspective, the tipping point of interest is when conventional energy sources are largely replaced by low-carbon or renewable technologies. Tipping points in technological adoption across a population of decentralized, individual users can occur through multiple mechanisms, including critical mass, diffusion of innovation, and social contagion, all of which center questions of human behavior, perceptions, and decisions **(Lenton et al., 2022)**. However, technological standards, policy regimes and the interests of industrial incumbents play an important role that can deter early adoption of new technologies, only to then support faster change once a process is underway **(Lenton et al., 2022)**. Primary industries have also received attention as they have several features that may predispose them to tipping points. For example, they are often concerned with intensely managed ecosystems whose structure has arisen through management actions rather than biophysical processes, likely making them more vulnerable to stressors **(Yletyinen et al., 2019)**. These systems are often centered around a relationship where the environmental component of the system provides a resource and the social component responds to changes (or perceptions of changes) in that resource level **(Mathias et al., 2020)**. Reviews of tipping points in primary industries have found that existing research largely consists of either conceptual exploration or individual case studies, limiting the degree to which this research could inform broader management **(Lauerburg et al., 2020; Yletyinen et al., 2019)**.

Across this literature, two defining features of SES tipping points are complexity and uncertainty. In SES, tipping points (and changes more generally) are mostly the result of multiple interacting factors and are rarely traceable to a single driver **(Winkelmann et al., 2022)**. For this reason, it may be misleading to refer to tipping points as being "climate-induced," when in reality, climatic conditions are mediated and influenced by social processes. In addition to multiple drivers, complex SES will likely exhibit multiple mechanisms and pathways toward tipping, as well as multiple potential post-tipping states **(Mathias et al., 2020; Winkelmann et al., 2022)**. This multitude of drivers, pathways, and impacts creates a high degree of uncertainty and unpredictability, particularly since social adaptive behaviors can drive responses to a given climate forcing and change the level of stress that the social system experiences. Because multiple actors exist within a system, classification of tipping points as positive or negative requires normative judgments that do not capture a diversity of values and may miss inequities in the distribution of outcomes **(Lenton et al., 2022)**. Finally, the interactions across multiple systems components (e.g., social, ecological, infrastructure, policy, etc.) require the integration of multiple types of expertise, each of which will have unique epistemological perspectives.

Due to this complexity and uncertainty, efforts to understand and influence SES tipping points can easily become convoluted and disorganized. This points towards the potential benefits of a conceptual framework that can assist in organizing collective thinking to identify key uncertainties, points of influence, and possible pathways of change. Conceptual frameworks can be regarded as organizational diagrams that summarize information on relationships and conditions in a standard, structured manner, assisting in understanding and explaining complex problems **(Gari et al., 2015; Patrício et al., 2016)**. These approaches have a long history in environmental and climate management contexts. For example, the driver-pressure-state-impact-response (DPSIR) framework has been widely applied in environmental management, although it has been critiqued for its limited ability to capture the full complexity of cause-effect relationships in environmental systems **(Patrício et al., 2016)**. The XLRM framework was developed to provide a formal approach for "intellectual bookkeeping" that could support long-term policy analysis under conditions of deep uncertainty **(Lempert et al., 2003)**. Conceptual frameworks can serve as problem structuring methods to provide decision support in situations where the performance measures, constraints and relationships between actions and consequences are not well defined or known **(Bell, 2012; Gregory et al., 2013; Mingers & Rosenhead, 2004)**. They facilitate interdisciplinary research by supporting a shared understanding of the problem definition, scope of inquiry, and relevant questions **(Hall et al., 2012)**. Finally, a consistent conceptual framework can provide structure that supports comparative analyses across locations and topics in a consistent manner, supporting broader insights than can be obtained from individual case studies alone **(Lauerburg et al., 2020; Yletyinen et al., 2019)**.

The objective of this manuscript is to define and present a conceptual framework for describing socio-environmental tipping points, using coastal communities as an example context. Previous research has developed conceptual frameworks for differentiating climate tipping points in social systems from those in biophysical systems **(Winkelmann et al., 2022)**. Here, we build on this prior work to develop a descriptive framework that provides a common baseline for understanding and describing climatic tipping point phenomena in SES. To this end, we first propose an organizational framework consisting of elements, state variables, links, internal processes, and exogenous influences that describes a SES subject to climatic pressures. This organizational framework is then used to define three potential modes by which tipping points could occur, including feedback processes, cascading linkages, and nonlinear relationships. We present the results of an expert panel review of the proposed framework, wherein coastal practitioners assessed the degree to which the framework could capture potential tipping points and inform research and planning needs. Finally, we present research priorities that could leverage this conceptual framework to advance knowledge of SES tipping points and identify actionable insights to inform adaptive planning and decision making.

2 An Organizational Framework for Describing SES Tipping Points

A well-defined organizational framework can provide structure for describing tipping points, support comparative analyses across different locations, and provide a foundation for computational modeling activities. We propose a system description of elements, state variables, links, internal processes, and exogenous influences. We also identify the following four key domains:

- Population: number of residents (permanent and temporary, e.g., students, tourists); demographic composition (e.g., age, race, income, and education); and socio-cultural characteristics such as community history, values, norms, attachment to place and sense of future possibility.
- Institutional: organizations with an influence over the system, including government at various levels (federal, state, local, military, and tribal), the educational system, non-profit and religious organizations, and community groups.
- Economic: businesses and industries; job opportunities and quality; real estate and other forms of wealth, assets, and debts (individual, public and private sector).
- Physical: natural and built environments, including forests, wetlands, and marshes; water bodies; homes and infrastructure; and places (e.g., beaches, parks, scenic landscapes and ancestral grounds) with emotional, spiritual, and recreational draw.

While deeply interwoven, we find that distinguishing these domains is helpful in enhancing the organizational and descriptive clarity of the model. However, we recognize that they are not independent of each other and overlap in many ways. For instance, a large employer within a community may have substantial influence on community politics and identity, exerting an institutional and cultural influence as well as economic. Thus, while we leverage the selected domains for descriptive purposes, they should not be considered exhaustive or fully independent.

2.1 Elements

Elements describe the actors, institutions, and physical assets in a system. For instance, in the population domain, elements include residents, households, and temporary populations such as tourists, students, or migrants. Within the institutional domain, elements include local government agencies and planning districts, public safety organizations, schools and universities, faith-based organizations, and civic or activist groups. Economic elements include businesses with a footprint in the community as either a source of employment, consumer opportunities, or services. Physical elements within a SES refer to the shoreline and water bodies, natural and built infrastructure, ecological resources, homes and buildings, land, and community spaces such as parks.

These elements will differ from place to place. For instance, communities with sizeable military bases will have economic opportunities, risks, and dynamics that would not occur in communities without this element. Rural communities often have different physical, institutional, economic, and social structures than urban areas. It is also important to recognize that many relevant elements may be partially internal to the community and partially exogenous. For example, a hospital or major employer might be located nearby but not directly within the community in question. However, they may still fundamentally shape the system in terms of people's day to day lives, through the provision of healthcare or employment opportunities. Thus, the bounds of the SES should not be considered purely spatial, but instead consider the influence or role that a given element plays in the community of interest.

2.2 State Variables

State variables describe the elements in an SES, typically at a single point in time, in terms of physical, institutional, economic, and socio-cultural characteristics. These state variables can describe a single element or population-level characteristics across multiple elements. A summary of potential state variables and the elements to which they apply are presented in Table 2. State variables are conditions that could conceivably be measured, even if practical challenges would make that difficult or infeasible. State variables in the population domain include those related not just to community population and demographics, but also to socio-cultural characteristics such as values and norms, community cohesion, inequity, capacity for engagement in civic actions, and environmental literacy. Values and norms are a particularly important population characteristic as they influence not just what types of resilience-building efforts are deemed palatable, but also those that are conceived of in the first place. Individual and community-level literacy and efficacy are key state variables that also influence community capacity for adaptation and resilience building **(Bey et al., 2020)**.

Another important state variable in the population domain is risk perceptions, as these may not be aligned with actual physical conditions. Perceptions are particularly important because even an expectation of a bad outcome could be sufficient to encourage large changes in social behavior **(Lenton, 2020)**. Conversely, if risk perceptions are misaligned with reality, that could also discourage a behavioural response. For instance, if people perceive that a location is safe due to the presence of flood protection infrastructure, they might be less inclined to take individual protective actions such as evacuation planning, building retrofits, or even deciding not to live in an area **(Pielke, 1999)**. Flood risk perceptions may be different in communities that experience regular nuisance or episodic flooding, which could normalize disruptions but also increase awareness or concern due to the frequent and visible nature of these events.

In the institutional domain, state variables include quantitative and qualitative descriptors of the organization's capacity and motivation to engage in resilience-building efforts. For example, organizational values, goals, and mandates might help identify the activities and efforts in which the organization could conceivably engage. Possible state variables to describe the capacity of an organization could be described by the tax base and other available financial resources such as the number of employees or members; the presence, absence, or capacity of incentive programs; and the means and degree of influence that an organization has within a community. State variables in the economic domain could describe the number of people employed or served by a business, as well as the financial precarity or resilience of the organization. In addition to the number of people employed by an organization, the nature of those jobs is likely to have an important influence on community susceptibility to tipping points. For example, workers in jobs requiring strict hours and physical presence might be at greater risk of losing employment if they are regularly late due to nuisance flooding compared to those with a more flexible schedule or the ability to work remotely. Possible state variables in the physical domain include land cover, building stock, elevation, and the presence and absence of infrastructure. Physical flood hazard and exposure are also considered physical state variables.

Domain	**Elements**	**State Variables**
Population	• Individuals • Households • Tourists or temporary residents	• Population size and demographics • Values and norms • Degree of cohesion/division, equity/inequity • Knowledge and efficacy • Risk perceptions
Institutional	• Government agencies • Churches • Schools • Health care facilities • Community organizations	• Capacity and resources • Influence • Number of members • Organizational values and goals
Economic	• Businesses • Banks • Real-estate	• Business community characteristics • Employment profile • Tax base • Availability of goods and services
Physical	• Land cover • Building stock • Shoreline • Built and natural infrastructure • Public spaces	• Distribution of land use • Age and condition of built assets • Shoreline characteristics (e.g., hardened or not, current mean tide levels)

Table 2: A non-exhaustive example of elements and state variables relevant for coastal risk and resilience across four domains.

2.3 Links

Links describe connections between elements within the system where a change in the state variable of one element would impact the state variable of another. Links can occur within and across domains, and consist of many different types of relationships, such as physical connections, financial interactions, cultural influences, and regulatory authority. Links can also be conceptualized by conditions where the functionality or wellbeing of one element relies on the functioning or wellbeing of another. Figure 2 presents a simplified example of potential links within a coastal SES that influence flood risk and resilience. For example, employment serves as a link between residents and businesses, whereas businesses that exist in reciprocal relationships with each other (for instance, farms, agricultural suppliers, and buyers cooperatives) would be linked through financial exchanges and potentially form broader economic industry in the community. Physical links exist between infrastructure systems (for example, water treatment or pumping infrastructure, which relies on electrical infrastructure), as well as within service relationships between infrastructure systems and the elements who use or rely on these systems.

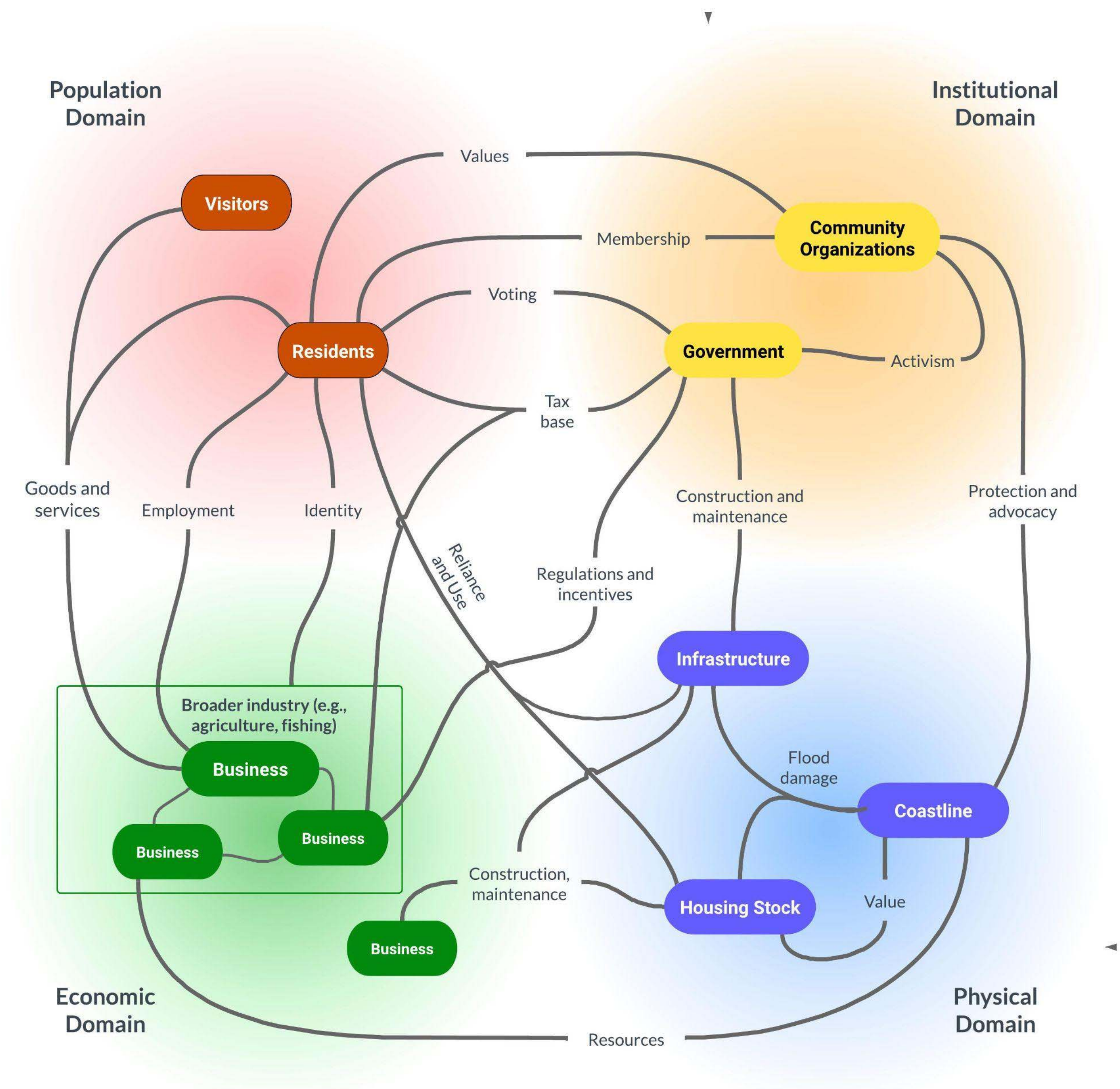

Figure 2: Example of links between different elements of a coastal SES. The figure is meant to show examples relevant to flood impacts and resilience building and is not intended to be exhaustive.

2.4 Internal Processes

Processes are the internal mechanisms and dynamics by which the elements and state variables change over time. These changes can occur through a process within the element itself, or by creating, strengthening, or weakening links between elements. Some processes may be internal to a single element, such as the financial growth of a business or industry that is only weakly linked with other elements in the community. Other processes will require links between multiple elements. For example, the process of land use change is a complex interaction between zoning decisions of regulatory institutions, housing market dynamics, and relocation decisions by individuals.

Because of the complexity and interconnectedness of SES, very few processes will impact a single domain independently. Still, we use the domain classification as a tool to describe the primary influence that different processes exert. Processes that most directly impact the population domain include in- and out-migration, as well as numerous socio-cultural processes that would impact the values, perceptions, and norms of a community in ways that have a direct impact on resilience. For instance, education is a process which can change community-level awareness and understanding of collective risks. Network or spreading processes among people and mediated by institutions and businesses can result in a departure from historically accepted practices to new behaviors or perceptions. Network spreading processes can be horizontal and spread across a single level (e.g., households) or more vertical with aggregation at higher levels (e.g., household to neighborhood to municipality). Examples of processes that most directly impact the physical domain include land use change and development, as well as infrastructure development, upgrades, maintenance and degradation. Institutional-domain processes include voting and other actions that result in changes to institutional actors, the operation and design of revenue collection programs, the development and operation of resilience-building or incentivization programs, and investment in community-strengthening organizations. Examples of economic processes include housing market dynamics, changes in employment opportunities, and growth or decline in the tax base.

2.5 Exogenous Influences

Exogenous influences are external factors that influence the state variables of the system, either directly or by influencing the internal processes of the system. While internal processes and exogenous influences are not entirely independent, we distinguish them by the degree to which actors within the system can meaningfully influence them. For example, sea level rise can effectively be considered an exogenous influence at the community level because it results from global-scale greenhouse gas emissions and ocean circulation patterns. However, the construction and maintenance of flood protection infrastructure and implementation of flood resilience efforts, such as evacuation planning or restricted development in flood-prone areas, can be considered internal processes because they are influenced by elements and actors within a community. Flood events are also exogenous influences, although the impact they have on a community is mediated by the elements present within the community (e.g., protective infrastructure, homes in at-risk areas, and community education programs), with their condition and effectiveness described by state variables. Other exogenous influences could include broad-scale economic drivers and trends that occur at a larger scale and filter down to community impacts, such as economic recessions, military base realignments, and enactment of federal regulations. Lateral exogenous influences could exist as well, such as the occurrence of a major disaster in a neighboring community that results in an influx of displaced people. Exogenous influences can be characterized as either chronic, long-term forces (e.g., sea level rise) as well as short-term sudden events (e.g., individual flood events).

3 Tipping Mechanisms in SES

Using a descriptive framework of elements, state variables, processes, links, and exogenous influences, we can describe three different mechanisms by which SES tipping points could occur (Figure 3). In the first, internal processes create feedback loops where the variables that influence a process are also affected by that same process. In the second, cascading impacts occur due to linkages within a system that lead to state variable changes in one element influencing state variables across many others. Finally, nonlinear relationships between state variables can lead to conditions where a relatively minor change in one variable results in a large change in a second. These different modes of tipping, as well as the manner in which they may interact, are described in the following sections.

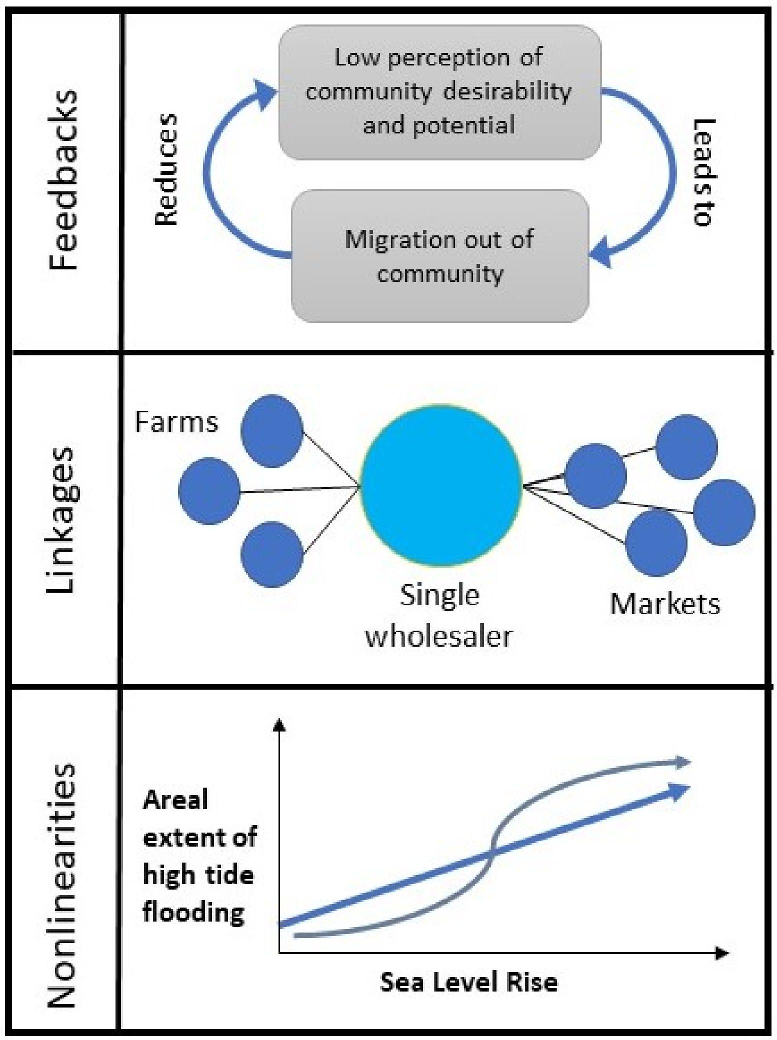

Figure 3: Mechanisms of tipping in SES.

3.1 Feedback Loops

Most processes relevant to climate impacts and resilience within SES will have multiple drivers (state variables that influence or contribute to the process) and impacts (state variables influenced by the process). These impacts can be directly influenced by the process in question, or indirectly influenced by linkages between system elements. Feedback loops can occur when the drivers and impacts of a process overlap; examples of processes with potentially overlapping drivers and impacts are presented in Table 3. Using in- and out-migration as an example, a classical economic view would assume that an influx of new residents to a community would increase housing demand and prices unless new home construction expanded the housing supply. This change in home prices could reduce demand for homes in the community, creating a dampening feedback loop. However, it could also fuel speculative property buying for investment purposes, amplifying price increases further and potentially contributing to gentrification if property tax and rental rates exceed the means of long-time residents **(Wilhelmsson et al., 2021).** Furthermore, a growth in the tax base of a community provides more resources for public-sector investment in infrastructure, schools, parks, and other community services, while population growth can also fuel the development of consumer businesses and amenities that further increases community desirability. These factors would then create an amplifying feedback, where continued community growth leads to more in-migration and the likely displacement of longer-term residents who can no longer afford to stay.

In general, dampening feedbacks would be expected to push a system away from tipping points, where amplifying feedbacks push a system towards tipping points. Many processes may be characterized by multiple feedback loops, some of which are amplifying and others dampening. In these cases, the relative strength of those feedbacks will determine the overall trajectory of that process and its potential for tipping. The relative strength of these processes are likely to be very context specific. For example, population growth fueled by increased job opportunities for low- and middle-income workers may be more sensitive to the dampening effect of increasing home prices compared to population growth fueled by high-income in-migration and speculative property buying. If these feedbacks can be quantified and measured, it may be possible to mathematically describe this balance between negative and positive feedback loops, determining an overall trajectory for the process. However, many processes may be challenging to quantify and measure, particularly those related to human perceptions, motivations, and understanding of risk and resilience. In such cases, it may still be possible to determine the functional form of the relationship between variables (e.g., linear, logistic, etc.) and the direction of feedbacks (amplifying or dampening) and make reasonable judgements about their relative strengths **(Barbrook-Johnson & Penn, 2022)**. This approach has been widely adopted in systems dynamics modeling, which consists of conceptual and quantitative methods used to simulate non-linear interactions and feedbacks among system elements, management actions, and performance metrics **(Elsawah et al., 2017)**. Even in contexts where limited data on system variables is available, systems dyamics models have been used to demonstrate the potential for regime shifts and tipping points **(Krueger et al., 2019)**.

Process	**Drivers**	**Direct Impacts**	**Indirect Impacts**
Migration in and out of community	- Housing availability and cost - Job availability and quality - Perceptions of community vitality and future prospects	- Population	- Tax base - Membership and capacity of community organizations - *Housing costs and availability* - *Perceptions about community vitality and possibility*
Industry-wide economic growth or decline	- Exogenous economic drivers (e.g. demand, commodity prices, presence of competitors) - Business innovation and agility - Regulatory environment and incentives - Resource availability (actual) - Resource availability (perceptions)	- Job availability and quality - Tax base - *Resource availability (actual)*	- Perceptions about community vitality and possibility - Population - *Resource availability (perceptions)*
Construction of flood protection infrastructure	- Damages and impacts of flooding (current and expected) - Perceptions of current and future flood risk - Resource availability - Regulatory will and capacity	- *Damages and impacts of flooding (current and expected)*	- *Perceptions of current and future flood risk* - Housing costs and availability

Table 3: Examples of processes where common drivers and impacts create feedback loops. Instances where a state variable is both a driver and impact of a process, creating feedback loops, are denoted in italics.

3.2 Cascading Linkages

A second mechanism by which tipping can occur is when cascading linkages across elements within the systems create the potential for a change in one element to impact others. Any complex system is defined by many linkages between system elements; thus, the presence of these linkages alone does not necessarily present an increased likelihood of tipping. However, there may be certain network structures that create a greater potential for tipping. The relationship between network structure and system change has been widely explored through the resilience lens. For example, the concept of centrality in social network analysis is used to describe nodes within a network that have a high degree of influence on the network as a whole

(Carrington et al., 2005). Changes to a highly central element of the system have a greater potential to cascade into system-wide impacts that influence many different elements. The notion of centrality within social network analysis can be integrated with physical and geographic system information to provide a broader view of system resilience **(e.g., Wang et al., 2020)**. Similarly, the presence of redundancy within a network can lead to greater resilience across infrastructure systems and supply chains **(Hesarkazzazi et al., 2022; Tan et al., 2019)**.

These concepts of centrality and redundancy could also describe the conditions where a small change in one system element creates greater potential for cascading impacts and system tipping. For example, consider an agricultural community where multiple farms are served by a single wholesaler who sells to multiple markets and buyers of farm products. This wholesaler would be a central node within the economic system, and the loss of this element, or even changes in their operations or capacity, would likely lead to broader impacts across farms and markets. Conversely, a community with multiple wholesalers would have a degree of network redundancy that reduced the chances of tipping if one business closes. Educational organizations can also serve as a central node within broader networks, connecting decentralized networks of peers and encouraging broader adoption of new technologies and practices.

3.3 Nonlinear relationships between state variables

A final mechanism by which tipping could occur is the presence of nonlinear relationships between state variables. In some cases, these nonlinear relationships may result from either feedbacks or linkages in the system, but these nonlinear relationships may also develop independently of these mechanisms. Coastal hypsometry, which describes the relationship between land elevation and sea level, is one example of a potentially nonlinear relationship that does not require the presence of feedback loops or cascading processes but could nonetheless lead to tipping point behavior. In a coastal landscape with a highly nonlinear hypsometric curve (e.g., an abrupt change in elevation), a small increase in sea level beyond a certain threshold would lead to a rapid increase in the area of land exposed to tidal flooding. Many coastal regions of the U.S. have been found to exhibit critical elevation thresholds where flood impacts to ecological and built resources become significantly more severe, with SLR projections indicating that nuisance flooding could regularly exceed these critical thresholds within decades **(Sweet & Park, 2014)**.

Nonlinear relationships will also likely exist in other contexts; for example, the relationship between business profit and number of employees will generally have a threshold below which the business closes down. In other contexts, a nonlinear relationship can arise from feedback processes or cascading linkages. One challenge in identifying these nonlinear relationships is that in complex SES, relationships between variables are rarely independent and there may be many instances where the relationships of interest cannot be easily mapped or quantified. However, even in these instances, it may be possible to qualitatively identify the conditions or thresholds where the relationship between variables would change in a significant way.

3.4 Interactions Across Tipping Mechanisms

The mechanisms of tipping presented above are not entirely independent, and tipping may depend on simultaneous processes. Nonlinear relationships may stem from the presence of feedback loops, or feedback loops may rely on the presence of cascading linkages between system elements. For example, if a municipality adopts a program to encourage home retrofitting, this could create additional elements in the form of businesses offering installation services, as well as new linkages between those businesses, early adopters, and later adopters who hire those businesses. The creation of these linkages then allows a feedback loop where visible customer satisfaction in the program drives more interest. However, there may also be instances where a single mode provides a sufficiently comprehensive description of the tipping point in question. For example, physical relationships between sea level rise and some measure of physical flood impact (e.g., the area exposed to spring-tide flooding) could point to tipping point thresholds. Feedback processes that are largely contained within a single element (e.g., one government agency) could create a potential for tipping that does not necessarily require cascading linkages across other elements. Thus, we present these modes as three distinct processes not to suggest that tipping points will always fit neatly into a single category, but rather to provide a framework for describing these tipping points and potentially identifying their dominant mechanism. Because different modes may be most compatible with certain analytical methods (e.g., systems dynamics modeling for feedback processes, agent based modeling or network theory for cascading linkages), this classification approach can also assist in identifying suitable approaches to better understand and project the tipping point in question.

4 Expert Review of Conceptual Framework

To obtain preliminary feedback on the conceptual model and the degree to which it could inform practice, we held a series of expert panel discussions with coastal practitioners from local and regional governments, private sector companies, and nonprofit organizations. Expert panels were comprised of ten professionals involved in coastal resilience in urban and rural communities in Virginia, and were interviewed in two sessions in May of 2023. The expert panel review was conducted using a semi-structured process adopted in previous evaluations of social tipping points **(van Ginkel et al., 2020; Winkelmann et al., 2022)** where participants collectively asked a common set of questions and then discussed those questions freely. Key themes from these discussions are summarized and discussed below.

4.1 Panel-identified tipping points

The first question presented to expert panel participants was, "*What are the issues or locations where you think tipping has or could potentially occur in the communities you are familiar with, and why?"* Participants identified multiple tipping points including changes in political will, updated regulations, economic changes, and infrastructure disruptions. In communities that had started implementing resilience measures, participants identified the point at which there was sufficient political will to move forward with projects as an important tipping point resulting from an accumulation of numerous small pressures and changes. These included increasing "pain points" as flooding resulted in land devaluation, lower tax revenues, and disruptions to everyday life, such as flooded roads and school closures. This tipping point also stemmed from changes in problem framing, with one participant stating that they were able to get political support for resilience measures only after they began discussing the problem in terms of the core governance tenets of protecting public health, safety, and welfare. Other panel members, particularly those representing smaller rural communities, considered this a prospective tipping point they still had not reached. In these cases, participants identified the importance of community education and outreach by locally credible individuals and organizations as a necessary step towards reaching a tipping point that would enable action.

A second type of tipping point identified by panel participants was regulatory changes either encouraging or hindering local-level resilience action. Participants pointed out that many existing regulations were created under very different circumstances than those we are experiencing now, and in some cases hindered the ability of localities or individuals to reduce flood risks. On the other hand, there are currently multiple opportunities that provide federal cost share for local-level adaptive measures. Participants noted that without these programs, localities would have to fully fund flood protection measures, likely leading to to increased retreat from at-risk areas. A third category of tipping point was economic transitions, particularly in the seafood and real estate industries. Participants noted that in certain waterfront industries such as seafood processing, regular flooding was creating an additional stressor to other challenges such as changing prices and labor shortages, making it increasingly difficult to remain in business. In communities heavily reliant on a single industry, the loss of these businesses could lead to much broader impacts. The real estate industry was also identified as a sector where tipping could occur. Tipping could stem from market changes, such as declining home prices in flood-prone areas, and industry decisions about where they will write mortgages and what risk mitigation measures must be in place. Finally, participants pointed out changes in infrastructure services as an issue that could contribute to tipping points. They were particularly concerned that private utility service providers, such as those that provide cable, internet, and electricity, could eventually decide to pull out of certain areas where providing services is challenging and costly. This could lead to significant impacts in rural communities with few, if any, alternative providers.

4.2 Conceptual Framework Feedback

The second question asked to the expert panel was, "*Do you think the mechanisms of tipping presented in our model would be capable of capturing these potential tipping points? If not, what is missing or unsuitable about the model*?" In general, the panel agreed that the mechanisms could capture the tipping points they had identified, but pointed out that the three modes were not independent and could occur simultaneously. Participants also noted desirable aspects of a conceptual framework that were not necessarily incompatible with the presented framework, but would need to be explicitly considered to support resilience planning. For example, panel members emphasized the importance of integrating economic, social, and physical components within any model, pointing out that social elements are very important but also difficult to measure and quantify. Representing economic outcomes, including changes in government revenue and the cost of inaction, was also viewed as a crucial component for identifying interventions. Effectively capturing social elements requires not only involving people with relevant expertise (sociologists, political scientists, psychologists, economists) but also developing model structures that can incorporate social components that cannot be quantified with confidence. Participants suggested various processes that could help achieve this, such as starting with a simple, narrowly focused model that was explicit about what variables were included and excluded; conducting a screening process in terms of what could be included with confidence; or developing a weighted or classification system that presented the relative impact of different drivers or processes without explicitly quantifying them.

Participants also pointed out the need for accurately reflecting complexities in physical coastal systems. For example, understanding the societal impacts of flooding and sea level rise requires not just data on the spatial extent of flooding, but more comprehensive information on flood frequency, duration, and depth. Participants also noted that interactions between chronic, repeated events and large floods are poorly understood as these events are often considered independently rather than as a suite of interrelated hazards that now commonly occur. Tidal wetlands were also identified as a physical element not often considered in its full complexity. For example, tidal wetlands play an important role in maintaining water quality, but their ability to do this is degraded by flooding. This can, in turn, lead to impacts such as beach closures due to contamination. The expert panel members noted that these impacts will occur earlier than damage to buildings and residences. Not only must an effective conceptual model capture this complexity, but it also needs to translate the outcomes into a policy-relevant format that can be communicated to various coastal audiences.

4.3 Panel Priorities for Research and Data Collection

The final question asked to the expert panel was, "*For the potential tipping points you identified, what are the uncertainties, data or research needs that present challenges in understanding or preparing for that tipping point?*" Multiple participants pointed out the need for more spatially detailed data not only on flood impacts but also on socio-economic data such as housing prices and characteristics, community risk tolerance, and willingness to pay for protective measures. For example, panel members pointed out that there could be differences in prices, insurance coverage, and the ability to sell property between waterfront properties and those a few blocks inland. There may also be neighborhood-scale differences in physical building characteristics (e.g., first-floor elevations, which often depend on neighborhood age) and economic characteristics (e.g., rental versus owner-occupied) that have large impacts on vulnerability and risk. A local focus is also needed to understand community tolerance for impacts and risk, as well as political will for adaptive actions. Differences across these factors mean that a tipping point for one community won't be a tipping point for another, and some places may be willing to expend significant financial resources to save a community, while others may not. Panel members noted local-scale differences in community values and preferences, such as the relative importance of private property rights or cultural history. Finally, participants noted local-scale differences in community risk perceptions, expectations, and history; for example, in locations where basic infrastructure services are not robust, communities may assume that increased flooding results from infrastructure deficiencies rather than sea level rise.

Expert panel members also noted the importance of developing a better understanding of recent changes and possible trajectories of economic and regulatory factors. For example, participants noted that there have been instances where insurance companies have revised their policies for homeowner insurance, and changes in the locations where federal flood insurance is provided. Understanding the factors that prompted these decisions would be helpful for communities in anticipating where similar changes might take place in the future. Finally, participants noted that regulatory policies and programs regarding resilience at the federal, state, and local level are generally uncoordinated. In the absence of this coordination, there is a need to identify effective strategies and potential risk reduction pathways that are feasible within this regulatory context.

5 Research Directions and Priorities

5.2 Priorities for Tipping Points in Coastal Communties

One of the clearest priorities to emerge from the expert panel review is the need for more comprehensive and salient understanding of the social, political, and economic factors that influence coastal risk and resilience. While the panelists noted some needs for physical system data that could support planning efforts (e.g., more comprehensive data on flood depth and duration; road flooding data; better understanding of the role of wetlands in coastal water quality), the bulk of the discussion centered on human systems, the substantial role that they play in resilience efforts, and the high degree of uncertainty in anticipating their behavior. This need for better understanding of human systems is mirrored more broadly; for instance, in agent based models of flood risk, structural uncertainty related to the way that human actions are simulated results in significantly more variability in model outcomes than parametric uncertainty **(Yoon et al., 2023)**. Thus there is a critical need for both additional data on human responses to flood impacts at the individual and institutional level, as well as approaches for integrating this information with physical flood risk data to inform planning. Reliable collection of data on human systems and behaviors is typically time and resource intensive; the use of the framework presented here could provide guidance in the types of data (e.g., those related to linkages and feedbacks) that could best improve understanding of tipping point dynamics. Nevertheless, complete characterization of complex human behavior and institutions is likely not feasible in many SES, and the urgent problems related to coastal risk and sea level rise cannot wait for this characterization to occur. Thus, there is a need for transparent analytical approaches that can simulate and explore the social and political outcomes associated with flooding and resilience building efforts despite the limited data available. Expert panelists suggested that even simple, qualitative models or descriptions of social, economic, and political elements could provide useful information, as long as researchers were clear about the limitations, assumptions, and factors excluded within these models.

5.1 Empirical Research and Foundational Understanding of Tipping Points

Moving from a conceptual perspective into more concrete knowledge that can inform adaptation practice will require empirical research and data collection that synthesizes insights across multiple SES **(Lauerburg et al., 2020)**. The conceptual framework presented here can help guide empirical efforts by suggesting areas on which researchers can focus their efforts to develop a better empirical understanding of processes, linkages, and nonlinear relationships between state variables.. One approach would be to include retrospective SES analyses that have undergone changes consistent with the tipping point concept, which could be evaluated to better understand how system features affect tipping point dynamics **(Winkelmann et al., 2022)**. However, retrospective analyses must move beyond individual case studies to produce more generalizable insights that can anticipate tipping points and identify interventions related to them. To this end, targeted efforts to collect comparable data across multiple SES using a common framework such as the one presented here could be beneficial in synthesizing information across different locations and contexts.

A greater empirical understanding of SES tipping point dynamics could also point toward the types of monitoring data that can best identify critical system states that precede tipping. Research in biophysical contexts has identified dynamic behavior often preceding tipping, such as a greater perturbation and slower recovery to shocks **(Lenton et al., 2019)**. However, it is unclear to what degree these insights can transfer to SES, where dynamics are less observable and predictable. Monitoring efforts to understand the trajectory of SES through time, and particularly of the social elements of those systems, would help determine if these warning indicators are present in SES and, if so, what conditions lead to more rapid change. However, many of the state variables associated with the population domain (Table 2) are not available in the socio-economic datasets often leveraged for climate impact assessment, such as the U.S. Census. More detailed monitoring of social data through time presents several methodological, logistical, and ethical challenges. Informing data collection and monitoring efforts in a conceptual framework such as the one presented here could assist in identifying the data types (e.g. real estate prices, social-media activity, use of community support services, flood assistance program claims, etc.) that could most effectively describe tipping potential. It is also important not only to monitor state variables within a system, but also people's perceptions of these variables. This is because these perceptions will likely guide public behavior and social system evolution, regardless of whether they align with the objective value of these variables.

Investigation into where the concept of tipping points sits within the broader context of resilience, sustainability, and social transitions could help determine if methods or concepts from these contexts could improve understanding and anticipation of tipping points. There is a broad literature on social and political system transitions and reorganization that focuses on fundamental system reorganization without requiring nonlinear or feedback-driven changes **(e.g., van den Bergh et al., 2019; Herrfahrdt-Pähle et al., 2020)**. This broader view of SES transitions may prove more impactful than focusing on tipping points alone, as it can contrast the conditions or characteristics associated with rapid, highly impactful changes (including tipping points) with those that lead to more gradual transitions or minor impacts. In comparing tipping points to resilience, tipping points could be considered an extreme case of a non-resilient system: a change which is unrecoverable, where the system never returns to the prior state. However, a key difference is that resilience is often centered on recovery to the existing stable state following extreme events, whereas tipping points definitions tend to include the notion that impacts can result from relatively minor contributing events.

5.2 Development and Use of Computational Models of Tipping Points

Computational models can serve an important role in managing SES complexity by facilitating the exploration of different alternative scenarios, assumptions, or management strategies. While integrated models that combine physical and social elements are common in climate impact analyses, a number of challenges undermine the degree to which these models lead to generalizable findings or support practical adaptation decision-making. Simulating interactions between multiple system components (e.g., natural processes, physical infrastructure, and human components), and particularly human behaviors that are difficult to predict or represent mathematically, introduces considerable uncertainty into computational models. Multiple methods exist for representing human behavior in integrated models, and the use of different approaches or parameterizations greatly impacts model outcomes **(Yoon et al., 2022)**. These issues and uncertainties undermine the degree to which models can be used in a classical consolidative or predictive approach, where data are consolidated to represent the best available projection of how the system of interest would evolve under certain conditions **(Bankes, 1993)**. However, it is still possible to leverage computational models in an exploratory sense, which begins with an acknowledgement that models of complex, deeply uncertain systems are unlikely to be effective as predictive aids or complete representations of the systems they represent. Instead, models are used as deliberative aids that can simulate complex phenomena, enumerate possible assumptions and outcomes, and systematically explore the implications of different uncertainties **(Moallemi et al., 2020)**. They can also help address cognitive limitations that hinder our ability to conceive of important systems-level features such as feedback loops, time delays, and nonlinearity by demonstrating the impact that these features have on system characteristics, behaviors, and outcomes **(Atkins et al., 2002; Brehmer, 1992; Sterman, 2002)**.

There are multiple ways in which exploratory modeling grounded in the framework presented here could improve our understanding and management of SES tipping points. For example, previous simulation research has demonstrated that multiple transition pathways can lead to tipping **(Mathias et al., 2020)** and that a capacity for regime shifts exists in urban water supply systems **(Krueger et al., 2019)**. Exploratory modeling could be used to identify these pathways and regimes, as well as the conditions that characterize them. The concept of pathways or roadmaps, which are potential sequences of adaptive actions that can be taken through time to respond to climatic changes, has been applied within the context of infrastructure adaptation **(e.g., Haasnoot et al., 2013; Lawrence, Judy et al., 2019)** and could be useful in identifying various pathways towards tipping points within SES. Exploratory modeling can also assist in identifying unintended consequences that can arise from interventions addressing issues within a single system component without considering their broader impacts. Even in biophysical systems, there are examples of interventions that ultimately had negative consequences (e.g., introducing species for pest control that become invasive). There is arguably an even greater possibility for unintended consequences in SES. Exploratory modeling can thus be used to elicit a range of possible outcomes to an intervention, as well as protective measures and adjustments that could guard against the worst outcomes.

5.3 Connecting Tipping Points Research with Practical Adaptation

Much of the motivation for researching tipping points is grounded in a desire to better understand the potential for severe climate change impacts and encourage positive changes to support climate mitigation and resilience. Therefore, it is important to pursue research that not just improves our foundational understanding of tipping points, but also supports policies and decision-making. One notable outcome from our expert panel review was that many of the tipping points identified by panel participants do not necessarily share the tipping point characteristics identified by the research community. For example, changes in political will or economic industries do not necessarily rely on feedback mechanisms. Thus, some degree of flexibility may be required among researchers aiming to support practical actions related to tipping points. The complexity and unpredictability inherent in SES tipping points likely undermine prescriptive approaches to decision support; however, existing decision-support methods aimed combining analysis with deliberative planning could be an avenue for actionable recommendations **(Lempert, 2019)**. Previous reviews have suggested multiple ways of "operationalizing" tipping points research to encourage positive change, including creating conditions that would enable desired tipping points, sensing the potential for a tipping point, and triggering this tipping **(Lenton et al., 2022)**. Similarly, **Winkelmann et al. (2022)** propose the notion of a "critical state," where a single or small number of actions can effect systemic changes. In this perspective, the event that triggers a tipping point is less important than the conditions that enable that change. Thus, identifying the strategic actions that can move a system towards a critical state is crucial in encouraging these transformations in practice **(Tàbara et al., 2022)**.

Finally, an important next step will be developing models and methods to embed the tipping points concept within processes for broader engagement across diverse groups of practitioners and stakeholders. The complexity and uncertainty that make predicting and modeling SES tipping points challenging also present difficulty in communicating these dynamics to general audiences. Developing of stakeholder-informed system maps to identify feedbacks and interconnections can support a more comprehensive view of potential tipping points **(Lenton et al., 2022)**. Computational models can assist in communicating complexity and uncertainty through activities such as serious games **(Flood et al., 2018)** and collaborative modeling **(Langsdale et al., 2013)**. While stakeholder involvement is crucial, it can also be demanding and require considerable effort from people with limited time to participate in research activities. Developing strategies to reduce the burden on stakeholders could facilitate their engagement with tipping point assessments. For example, the time and effort required from the stakeholders could be reduced by developing archetypes of tipping points that discuss their enabling conditions and modes of tipping but can be adjusted to individual contexts.

6 Conclusions

The concept of climatic tipping points in socio-environmental systems is gaining interest as a potential mechanism for understanding and, in some instances, encouraging rapid shifts in response to climate change. This work presents a conceptual framework for describing climate-related tipping points in socio-environmental systems. We use a descriptive framework consisting of elements, state variables, processes, linkages, and exogenous forces as a means to describe SES. Within this framework, we consider three mechanisms by which tipping points could incur: feedback processes, cascading linkages, and nonlinear relationships. An expert panel reviewing this framework found that it could be used to describe past and future tipping points observed in their professional experience. Namely, they identified four critical tipping points in coastal systems challenged by flooding and sea level rise: political will, regulatory changes, economic transitions, and infrastructure services. Experts also pointed toward several challenges in representing and anticipating these tipping points, including the need for a more sophisticated representation of social, political, and economic processes. This points towards several priorities for future research that could improve the understanding of tipping potential for risk reduction and transformative adaptation. These priorities include a better empirical understanding of tipping processes in SES; the development and utilization of computational models that can provide insight into tipping potential and simulate potential outcomes of interventions; and developing methods for translating tipping point research into practical decision making. We propose the descriptive framework presented here as a common baseline for structuring future research on climate-related socio-environmental tipping points that can ultimately support transformative adaptation in the face of climate change.

Acknowledgments

The authors declare no real or perceived financial conflicts of interest or affiliations that may be perceived as having a conflict of interest with respect to the results of this paper. This work was financially supported by a grant from the Virginia Tech's Center for Coastal Studies. We would like to thank expert panel participants for their valuable contributions and insights.

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No specific data were created for this manuscript.

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