Research Opportunity
Identifying Tipping Points Across Biological, Physical, and Social Systems

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I. What is a tipping point?

A tipping point is generally defined by a critical change in a complex system resulting from small changes in the drivers and/or external conditions. Even before crossing a tipping point, a system may become increasingly vulnerable to perturbations due to loss of resilience. A tipping point may be irreversible. Tipping points can occur in a physical system (e.g., irreversible melt of the Greenland ice sheet), ecological systems (e.g., bleaching of the Great Barrier Reef), bio-geomorphic systems (e.g. mass drowning of salt marshes, massive loss of seagrass meadows in the North Sea, disappearance of barrier islands), societies (e.g., collapse of civilizations, mass migration), and in the built environment (e.g., ageing infrastructure with lack of investment to repair). However, in many cases, a tipping point in one system often has significant implications for other, interconnected systems. Though a tipping point in climate change research often refers to an undesirable state or negative consequences, it can also be beneficial (e.g., energy market transformation from renewable energy expansion).

II. Why is this research important?

Coastal systems are changing rapidly in response to multiple factors including changing environmental conditions, economic activities, societal expectations, and the effects of both legacy and new infrastructure. The pace and magnitude of this change can force decision makers to be reactive, and implement local, temporary solutions that can have long-term and far reaching consequences. A well-studied example is shoreline armoring, often by individual property owners, in response to erosion by waves. Not only does such armoring disrupt supplies of sand and gravel that forms and maintains adjacent beaches, but erosion can both result in the creation and destruction of essential habitat for species (e.g., migratory fish). Once sandy beaches become rocky, the character of the shoreline is fundamentally changed.

The overall objective of studying tipping points is to understand the dynamics of key components of coastal community systems (Section III) and interactions and feedbacks among them to provide a more holistic view of coastal system dynamics. Predicting how these interactions and feedbacks change, as a result of perturbations by episodic events (e.g., hurricanes, tsunamis) or pressures from chronic or acute stressors (e.g., sea-level rise, economic transitions, aging or inadequate built infrastructure), enables identification of key tipping points within the system. Interpretive tools can then allow decision makers to foresee the consequences across the system. Some adverse consequences may be avoided by strategic investments (e.g., selected retrofit of infrastructure or habitat restoration, planned adjustments in the human environment, relocation of essential facilities to ensure continued service provision). Others may force a rethink of a communities' future and reworking of local policies or ordinances to be better prepared. Examining the potential for tipping points at this holistic scale, developing tools that integrate the dynamics of natural -social and economic subsystems and interactions among them, supports future coastal resilience by guiding investments, enabling communities to transition, and supporting a proactive approach to future, sustainable coastal development.

III. Integrated Coastal Systems

Disruptions to communities can be infrastructure-damage driven, but could also be social, economic, or ecological disturbances, among others. Each of these systems has complex internal feedbacks than can lead to tipping points, beyond which they rapidly deteriorate and disappear, even without a particularly large disturbance. For clarity, below we distinguish between each component of the integrated coastal system (Figure 1, left).

Biotic: Biotic systems include the flora and fauna that make up coastal ecosystems (e.g. intertidal wetlands and mudflats, seagrasses, kelp forests, coral reefs, and pelagic ecosystems). Many of these ecosystems are able to bioengineer habitats and thus impact the abiotic environment. For example, marsh vegetation can promote accretion, thereby maintaining elevation in the fact of sea level rise.

Abiotic: Coastal landscapes and the ecosystems their support (e.g. barrier islands, beaches, dunes, coastal lagoons, wetlands, and intertidal, benthic, and pelagic zones) are the result of complex interactions between physical drivers (waves, tides, water currents, wind), sediment transport and topography. In many cases, those landscapes are shaped by biotic-abiotic interactions and feedbacks.

Social: Social systems at the coast are diverse including traditional culture and residents with coast dependent livelihoods, temporary populations of tourists and large urban-industrial port cities. Demographic and social character will influence community dynamics, vulnerability and interdependence with other components.

Economic: Coasts support a range of economic activities and services (global trade, tourism, aquaculture, etc.) which can be specifically coast-dependent (e.g., ports), take advantage of other local resources (e.g., agriculture), or may reflect legacy economic activity that relied on coastal locations for transportation (e.g., logging).

Built Environment: The built environment comprises of the physical infrastructure needed for the society to function and for its well-being. This could include residential dwellings, roads, bridges, hospitals, schools, water treatment plants industrial, and commercial facilities.

Interactions and feedbacks in the integrated coastal system: Many of the most relevant coastal ecosystems and morphologies have internal feedbacks that lead to tipping points in the external conditions, beyond which they rapidly deteriorate and disappear, even without a particularly large disturbance. Furthermore, those ecosystems do not exist in isolation but influence each other and also co-exist with, and provide services to, local communities and the build environment. As a result, tipping points in natural systems are not only strongly influenced by human activities but their effects can also propagate to the build environment and the socio-economic structure and trigger a large-scale deterioration in the system resilience to external events and the long-term sustainability of the whole system.

When considering infrastructure damage, one can consider the main infrastructure sectors that are critical to the functioning and well-being of communities. Several lifelines can be important to communities (e.g., Figure 1, right). Interactions among the lifelines can be classified as unidirectional or bidirectional and the strengths of those interactions can vary. Each lifeline is dependent on at least one other and their interactions play a vital role when considering recovery of a community.

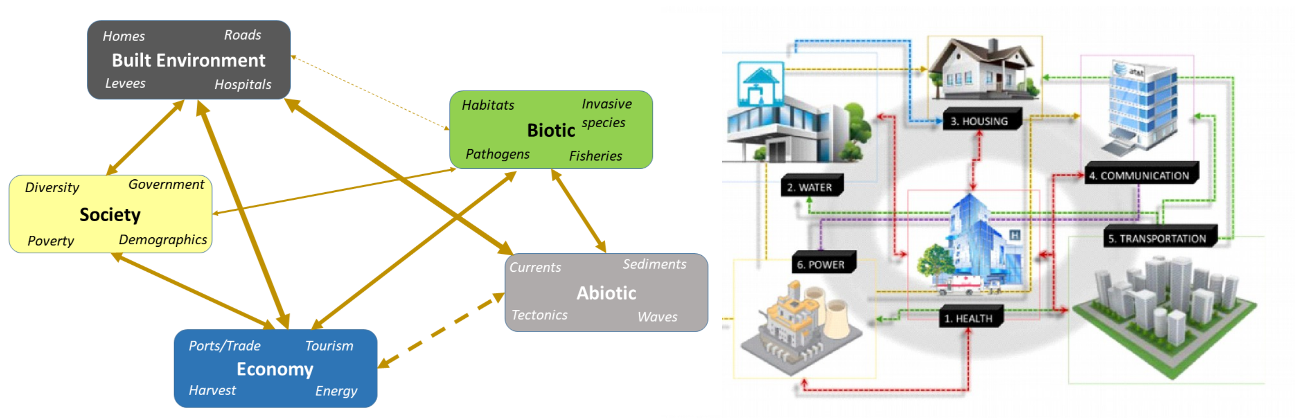

Fig. 1. Conceptualization of the coastal system and interactions among subsystems (left) and interdependencies of infrastructure lifelines with each other in a community with the direction of arrow determining lifeline being supported (right) (Mahmoud and Chulahwat, 2018).

IV. Challenges to conducting the research

Broadly, we see three primary challenges to conducting this research.

Data Poor Systems: There are few data of the response of the system, and its different components, to a large enough range of internal and external perturbations, and along multiple spatial and temporal scales, to be able to investigate the propagation of perturbations, understand the nature of the connections between the subsystems and predict topping points.

Complex Interactions: The complex network of interactions among the different components of the coastal zone, and the two-ways interactions leading to feedbacks and potentially controlling or defining system-wide tipping points is largely unknown at the scope of the system shown in Figure 1a.

Lack of Common Frameworks: Often, there are no common conceptual and/or modeling frameworks to integrate the dynamics of the physical, biological and social components of the coastal zone; the subsystems have historically been described using very different approaches.

V. Recommendations to address these challenges and further the research

To identify tipping points and the causes of fundamental change in coastal systems, scientists need to characterize the driver-state relationships for each component of the integrated system, the key variables, and the feedbacks and connectivity among components (Figure 1a). This work requires:

(1) Long-term time series

Long-term data is needed to characterize the temporal dynamics of the system and to detect and diagnose fundamental changes in system dynamics. Existing monitoring programs can be leveraged (e.g. LTER, NEON, Ocean Observing Systems). Time series of remotely sensed earth observations (e.g. Landsat, MODIS) provide a means for observing changes over large areas on multi-decadal time scales which is valuable, as systems may exhibit spatial heterogeneity in their response to drivers. Socioeconomic data (e.g., income distribution, poverty rate, education, governance) need to be integrated, and quantitative and qualitative tools applied to consider different social groups and economic components.

(2) Controlled and natural experiments

Controlled experiments, including those based on simulations, can be used to test the response of systems to a range of perturbations (both chronic and acute), and determine whether subsequent changes in system dynamics are reversible. Documenting 'natural experiments' (e.g. hurricanes, earthquakes, economic shocks) can enable learning about phenomenon that cannot be easily manipulated.

(3) Scenario planning informed by case studies and historic examples

Scenarios can describe plausible conditions for key drivers of each component (e.g., economic growth, infrastructure development, land use change, migration) and key state variables of both individual component and the connected system. Scenarios can be selected based on specific case studies and historic experiences (e.g., societal collapse). Lessons learned from past disturbance events (historical knowledge) can also be used in scenario development.

(4) Novel modeling approaches

Comprehensive integrative models must be developed to account for feedbacks and interactions among physical, biological, economical, and social components of coastal systems. The models should be generalized and easily configurable for any community while considering the spatial as well as the temporal variation of community's ability to cope with tipping points of all sectors that make up communities and their interdependencies. There are significant advancements in modeling of individual components or systems (e.g., coastal ecosystems, economic activities, infrastructure) and frameworks are emerging to connect individual components within a system to represent its dynamics and connections at finer scales. The development of integrative models could occur via the creation of an Opensource Simulation and Visualization Hub serving as a centralized entity for developing advanced integrative models using a system of systems approach.