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A Resilience Framework for Chronic Exposures: Water Quality and Ecosystem Services in Coastal Social-Ecological Systems

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ABSTRACT

Water quality degradation is a chronic problem which influences the resilience of a social-ecological system differently than acute disturbances, such as disease or storms. Recognizing this, we developed a tailored resilience framework that applies ecosystem service concepts to coastal social-ecological systems affected by degraded water quality. We present the framework as a mechanism for coordinating interdisciplinary research to inform long-term community planning decisions pertaining to chronic challenges in coastal systems. The resulting framework connects the ecological system to the social system via ecological production functions and ecosystem services. The social system then feeds back to the ecological system via policies and interventions to address declining water quality. We apply our resilience framework to the coastal waters and communities of Cape Cod (Barnstable County, Massachusetts, USA) which are affected by nitrogen over-enrichment. This approach allowed us to design research to improve the understanding of the effectiveness and acceptance of water quality improvement efforts and their effect on the delivery of ecosystem services. This framework is intended to be transferable to other geographical settings and more generally applied to systems exposed to chronic disturbances in order to coordinate interdisciplinary research planning and inform coastal management.

KEYWORDS
Ecosystem services; resilience; water quality

Introduction

The same natural amenities that lead people to live and recreate along coasts can be degraded by that very proximity and social demand for ecosystem services. The human footprint on the environment is considerable in coastal zones (Halpern et al. 2008), especially with regard to water quality (Doney 2010). Coastal communities' ability to respond to and mitigate these impacts in order to maintain a reliable quantity and

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quality of ecosystem services represents a critical feedback mechanism necessary for the resilience of social-ecological systems. Concepts such as ecosystem services and social-ecological systems are increasingly being used to translate many of these complex interactions into frameworks and models that describe the organization and management of natural resources (Yoskowitz and Russell 2015; Biggs, Schlüter, and Schoon 2015; Collins et al. 2011). A social-ecological systems approach (Berkes and Folke 1998) requires researchers across diverse social and ecological disciplines to engage in integrated assessments to resolve natural resource management problems (Carpenter and Gunderson 2001).

In this study, we describe the application of resilience concepts to social-ecological systems research, specifically to water quality issues in coastal systems. We develop a resilience framework which incorporates ecosystem service concepts to better understand components of coastal social-ecological systems affected by water quality degradation. Resilience in the context of this paper is defined as the capacity of a system to absorb disturbances and respond to change while providing the same or similar ecosystem services provided through the system's function, structure, and feedbacks (Scheffer et al. 2001; Holling 1973). We highlight the important features and gaps in coastal social-ecological systems that impede social action to address nutrient challenges in coastal waters. By using our approach, research can be more appropriately directed to fill knowledge gaps to inform and facilitate management decisions that may lead to enhanced resilience of the system. We discuss the framework in application to Cape Cod's ("the Cape;" Barnstable County, Massachusetts, USA) coastal waters and communities and the impacts of nitrogen over-enrichment. The framework is intended to be useful to researchers and managers in other coastal settings and more widely applicable to social-ecological systems exposed to chronic disturbances.

Water quality problems resulting from excess nutrient inputs tend to be complicated, long-term challenges for a number of reasons. Nutrients are essential ingredients for primary production and the production of some ecosystem services will benefit from small amounts of nutrient addition, making it challenging to determine how much nutrient addition is ecologically destructive or socially unacceptable. Frequently, nutrient inputs are from non-point sources and may originate far from the impacted waterbody, making it difficult to connect source to effect. Distant sources of nutrients may take months to decades to reach impacted water bodies, so problems can develop slowly over time. In addition, there are significant time lags between action to mitigate the problems and the realized benefits of doing so (Underdal 2010).

Chronic stressors, or disturbances that are gradual and build over time, are sometimes characterized as slow-impact hazards or as pressures (Cutter et al. 2008). Such disturbances persist across long time periods and impacts can accumulate slowly, preventing opportunities for recovery (Nyström, Folke, and Moberg 2000). Some examples of chronic stressors that affect the resilience of social-ecological systems include water supply issues (Milman and Short 2008), sea-level rise, temperature increases, and the impacts of water quality degradation (Duh et al. 2008; Gunderson et al. 2006; Cottingham and Carpenter 1994). The key differences between an acute and a chronic exposure relates to the magnitude and duration of the exposure. While an acute exposure might be of high magnitude and occur over a short period of time, a chronic exposure is continuous or continuously repeated. We refer to nutrient over-enrichment as a chronic exposure in this study because of the constant nature of the input, associated time lags, and often slow ecosystem response.

Due to their slow-onset time, these chronic stressors may provide the opportunity for communities to mitigate and/or adapt in a way which maintains the social-ecological system's structure and function (Cutter et al. 2008). However, experience shows this does not necessarily mean mitigation or adaptation will happen or has happened. Because of the breadth of challenges facing coastal systems and the uncertainty in the cause and effect of interventions, environmental managers rarely have the opportunity to be sufficiently proactive in mitigating or reacting to chronic problems. Research designed to overcome these management challenges can enhance the resilience of a social-ecological system by strengthening the primary stabilizing feedback loop, as described in this paper, between the social and ecological systems. This feedback loop is the ability for the social system to respond to changes in ecosystem services through implementing policies and interventions to address chronic stressors.

Methods

In order to develop a useful resilience framework to investigate long-term, nutrient-induced water quality degradation, we synthesized a wide range of literature and incorporated concepts from existing frameworks. Our team consisted of a number of different fields of expertise including ecologists, biologists, economists, social scientists and decision analysts. As a group, we reviewed relevant theories and systems approaches for understanding the social and ecological elements of resilience. Below, we present the results of our literature review and framework development. We then explain our framework through an application to Cape Cod's estuaries and communities and describe its potential for developing integrated research programs.

Resilience

As defined above, our use of the term "resilience" encompasses concepts of resistance and recovery potential. Natural and social systems have components, functions, and feedback loops that provide resistance from changes to disturbances as well as the ability to respond to change while maintaining some dynamic equilibrium. Take, for example, two hypothetical dynamic equilibria, represented by different basins of attraction (Figure 1; Biggs, Schlüter, and Schoon 2015; Folke et al. 2004; Holling 1973). These dynamic equilibria could represent either the social system, ecological system, or the entire connected system. In the context of this paper, these basins represent a system in a desirable equilibrium defined by a high provision of ecosystem services and a second possibly stable, but undesirable equilibrium with degraded ecosystem services.

There are a number of effects on social-ecological systems from chronic disturbances such as anthropogenic nutrient loading. Chronic disturbances move it away from its original dynamic equilibrium point (represented by the large arrow in Figure 1b) and erode the resistance of the system, represented by a shallowing of the basin (Figure 1b). This erosion of the resistance of the system makes it more likely that the system will be perturbed to the point that it passes a tipping point and trends towards an alternative dynamic equilibrium (1 to 2 in Figure 1b). As a consequence, the erosion in resistance that results from chronic disturbances leaves the system more vulnerable to acute disturbances. It may also inhibit recovery due to the cumulative effect the stressor had on the system. Recovery is represented by returning towards and enhancing the stability of a desirable equilibrium (Figure 1c). The ability to resist change coupled with the ability to recover are both elements of the resilience of the social-ecological system.

The resilience of coastal social-ecological systems can be affected by a number of different stressors (Van Oudenhoven, Mijatović, and Eyzaguirre 2011), ranging from acute events to the more chronic impacts such as water quality degradation, coastal erosion and climate change. A considerable body of resilience literature has been developed for acute events that integrates both the social-ecological systems and ecosystem services literature (e.g., Brose 2015; Cimellaro 2016; Cutter 2016). However, a similar body of work addressing chronic problems has not been concurrently developed. Typically, resilience to chronic issues is considered only from the perspective that the ongoing subtle impacts may eventually lead to sudden, drastic changes because of the loss of resilience in the system (Scheffer et al. 2001; Cinner et al. 2013).

Water quality and resilience

There is little work connecting water quality and resilience in social-ecological systems. Past studies related to water quality and resilience have focused primarily on the ecological impacts of water quality rather than overall system impacts, including social impacts. In addition, the studies mostly focus on the degradation of freshwater lakes and wetlands (e.g., Brookes and Carey 2011; Gunderson et al. 2006; Cottingham and Carpenter 1994; Cottingham and Carpenter 1994). In one of the early works in temperate lakes, Cottingham and Carpenter (1994) developed predictive indicators of ecosystem resilience and found the planktivore-dominated food web to be more resilient at low nutrient loadings, but the piscivore-dominated food web to be more resilient at the highest nutrient loadings. Carpenter and Cottingham (1997) found degraded lakes to be less valuable than normal lakes, highlighting the value of restoration for resilience of

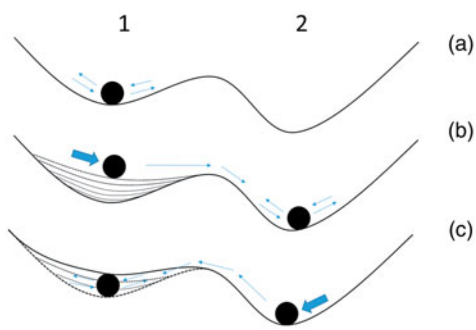

Figure 1. Dynamic equilibrium shifts in social-ecological systems. Note. The basins represent two possible dynamic equilibria (1 and 2). The three variations represent: (a) a system in dynamic equilibrium, (b) a chronic stressor perturbing the system and eroding resistance, (c) recovery from a chronic stressor. The figure was adapted from Proença and Fernández-Manjarrés (2015) and Folke et al. (2004).

social-ecological systems dependent on the lakes. Gunderson et al. (2006) compared linkages across social systems and ecological systems centered around lakes and wetlands, highlighting the need for productive learning, trust, and leadership within the systems. Brookes and Carey (2011) discuss the need for considering multiple factors that favor cyanobacteria in the management of freshwater systems, including climate change and nutrients.

The limited body of work that evaluates the impact of water quality on the resilience of marine systems and coastal communities is primarily focused on tropical waters, coral reefs, and seagrass systems. In a review article, Folke et al. (2004) connected a loss of resilience resulting from emissions of waste and pollutants to an increased possibility of the system shifting to alternate steady states. The authors highlighted the possible synergistic impacts of the chronic pollutants with acute stressors, such as disease or storms. Hughes et al. (2003) reviewed the importance of management strategies that support coral reef resilience to allow for the change due to climate change and coral bleaching. Adger et al. (2005) discussed social-ecological resilience to coastal disasters and described the complex feedbacks between economic output, water quality, and coral reef health. Water quality and overfishing are discussed as contributing to the erosion of the resilience of the systems, thereby impacting the capacity to cope with disasters.

Nyström, Folke, and Moberg (2000) highlighted the synergistic impacts of chronic nutrient pollution on coral reefs with overfishing and natural disturbances. They discussed the differences between persistent human-induced and pulsed natural disturbances, noting that with persistent, accumulated disturbances, there is little time for recovery. In their framework for the resilience of seagrass ecosystems, Unsworth et al. (2015) examine a number of different stressors to seagrass systems, including water quality degradation, and connect those stressors to ecological regime shifts. They also identify management actions that can be implemented to interact with the influence of those stressors.

Applications of social-ecological systems resilience concepts related to quality degradation in temperate coastal systems are not well-represented in the literature. The chronic nature of nutrient induced water quality degradation and the long lag times between social action and ecological impact does not fit well into most traditional resilience frameworks. As a way to organize research, some options for frameworks were not useful to one research discipline or another, or do not have easily translatable concepts that were meaningful in both the social system as well as in the ecological system. Therefore, our objective was to formulate a new framework for chronic exposures, specifically for water quality challenges.

Framework development

We developed a framework for investigating long-term nutrient exposure leading to water quality degradation through a holistic view of resilience, encompassing outcomes of and feedbacks between the natural and social systems. We then applied the framework to direct interdisciplinary research intended to overcome gaps in knowledge of the system that inhibits effective coastal water quality management. We applied the work of Cinner et al. (2013) and Marshall et al. (2010) to connect social and ecological vulnerability of a marine system to a chronic change, although their work primarily discussed resilience in terms of acute events. We used ecosystem services to connect the ecological system to the social system, following the framework described by Wainger and Mazzotta (2011). Specifically, we used the final ecosystem goods and services (FEGS) construct (Landers and Nahlik 2013; Johnston and Russell 2011). Following Cumming et al. (2005), we incorporated temporal dynamics and acknowledged the importance of drivers external to the system of interest. We made a point to specifically include the resilience of the social system in addition to the ecological system and used Cutter et al. (2008), to describe social resilience at a local level. The process of problem identification, defining resilience components, determining the important interactions in the social-ecological system, and broadening the context to be applicable to other potential chronic stressors, resulted in the framework presented in this paper.

Site description

Cape Cod includes fifteen towns, each of which has a number of estuarine and open-water beaches that are important to the quality of life of year-round and seasonal residents and are drivers of the tourism-based economy. Of the 53 distinct estuary embayment watersheds across the Cape, 38 have been identified as having nutrient-related impairments as of the fall of 2017 (Cape Cod Commission 2017a). Excess nutrients, especially nitrogen, can cause increased production of algae, epiphytes and macroalgae that, in turn, lead to other secondary symptoms of eutrophication (Bricker et al. 1999) such as periodic algal blooms, fish kills, and unpleasant odors. This is largely the result of nutrient loading from on-site waste water treatment systems (septic systems, including cesspools; Cape Cod Commission 2015; Howes, Samimy, and Dudley 2003). Excess algal growth leads to reduced aesthetic quality of coastal areas and it affects the quality or availability of recreational opportunities for the adjacent communities.

The Federal Clean Water Act requires the state of Massachusetts to identify impaired waterbodies and estimate the total maximum daily load (TMDL) of a pollutant that would resolve the impairment. On average for the estuary systems on the Cape, nitrogen loading needs to be reduced by 32% to achieve the TMDLs (Cape Cod Commission 2015). Towns are considering a combination of sewering and alternative approaches including the use of shellfish aquaculture and shellfish seeding, permeable reactive barriers, and localized wastewater treatment technologies to meet these nitrogen load reductions. The performance of these alternative technologies to reduce nitrogen, their social acceptability, and their costs complicates decisions on where, when, how, and to what extent to use them in meeting the TMDLs (Cape Cod Commission 2017b).

Results

Our resilience framework for chronic exposures consists principally of the primary feedback loop between the ecological and social systems, as connected through ecosystem services and policies and interventions (Figure 2). It reflects the steps in a possible adaptive management process that leads the system to trend towards one dynamic equilibrium or another depending on the strength and timing of this feedback loop and

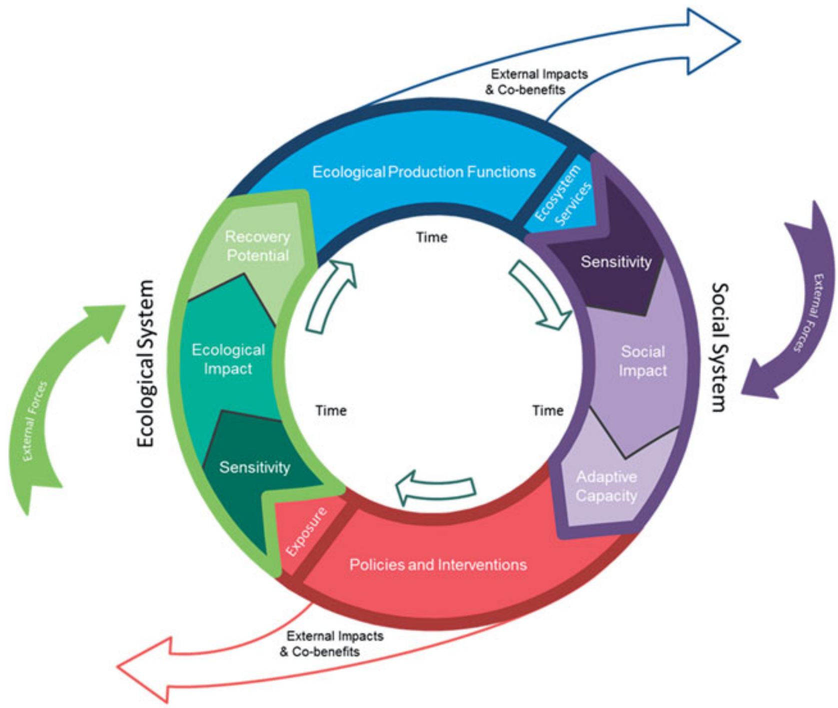

Figure 2. Social-ecological system resilience framework for chronic exposures. Note. The circular nature of the framework represents the connections between the social system and the ecological system as well as the primary stabilizing feedback loop of the overall social-ecological system. The elements of the framework are defined in Table 1 in a water quality context and applied to the Cape Cod social-ecological system.

the functioning of elements of the system. We purposefully maintained parallel concepts between the ecological system and social systems (exposure: ecosystem services, sensitivity: sensitivity, ecological impact: social impact, and recovery potential: adaptive capacity) for the benefit of making them analogous to those concepts that are closer to any one team-member's field (Figure 2 and Table 1). The terms defined specifically for use in this framework are italicized and bolded where they are defined in the text. The intention of this layout is to clarify the causal chain from any one component to the overall function of the social-ecological system and its resilience. Below, the elements are discussed within the context of the Cape Cod social-ecological system and its nutrient issues.

Nitrogen enters the ecological system as an *exposure* resulting from the social system's existing policies and practices for producing and treating nitrogen. On Cape Cod, the greatest proportion of nitrogen is from insufficient wastewater treatment (primarily the result of septic systems, including cesspools). Nutrients dissolved in wastewater enter the groundwater and coastal waters over varying time frames depending on where they were emitted and the speed of groundwater flows. Due to the geology of the Cape, groundwater travel times from septic systems to the embayments on Cape Cod range from essentially zero for properties abutting the embayments to more than 100 years for properties further inland (Walter, Masterson, and Hess 2005). The uplands-coastal system has a natural ability to attenuate some of these nutrient flows. However, the

Table 1. Resilience and social-ecological systems terms used in this framework.

	Term	Description	Cape Cod research
Ecological system	Exposure	Type and amount of anthropogenic water quality stressor into a waterbody	Concentration, scale, duration and identity of nitrogen
	Sensitivity	A waterbody and its components' susceptibility to harm, or the exposure-response relationships among physical-chemical stressor(s) and the structure and function of the ecosystem	Size and hydrodynamics of the waterbody, biomass, species abundance and richness, habitat types
	Ecological impact	Structural and/or functional change of a waterbody in response to the interaction of exposure and sensitivity	Seagrass loss, marsh area changes, fish kills, algal blooms and declining species richness and functional traits
	Recovery potential	The ability of the ecosystem to return its structural and/or functional condition over time to a high functioning or minimally-disturbed condition given a reduction in exposure	Substrate nitrogen remobilization, enzyme activity, water quantity and timing (flushing flows), groundwater delay time, benthic nutrient stocks and functional redundancy
Ecological Production Functions		The translation of ecological system structure and function to outcomes relevant to the social system.	
Social system	Ecosystem services	The components of a waterbody directly enjoyed, consumed, or used by the community	Water clarity, recreational shellfish stocks, finfish, clean shorelines, and bottom conditions.
	Sensitivity	The community's susceptibility to harm, or how dependent the social and economic system functioning is to changes in ecosystem services	Market and non-market values for water recreation, percentage of tourism-related jobs in a community, and number of alternative locations for water recreation; social preferences
	Social impact	Structural and/or functional change of social and economic factors in a community in response to changes in ecosystem services	Loss or gain of recreational enjoyment, well-being, sense of place, tourism revenue and jobs, and property values
	Adaptive capacity	The ability of a community to respond to or cope with changes in ecosystem services	Innovation in water quality infrastructure, social trust and networks, financial power, and governance
Policies and interventions		The behavior and actions that result in changes in exposure to the ecosystem	Installation and maintenance of nitrogen load reducing technologies, in-estuary restoration and other nitrogen mitigation efforts

system's capacity to remove excess nutrients is not unlimited. When the waste from the local population exceeds this assimilative capacity, excess nutrients reach the estuaries.

Sensitivity of the ecological system is an estuary's (or its components') susceptibility to harm from nitrogen exposure. Generally, and on Cape Cod, estuaries are nitrogen limited causing sensitivity to influxes of changes in loading (Nixon 1992; Valiela et al. 1990; Tomasky et al. 1999). The influence of nitrogen on the system is based on a number of factors including hydrodynamics of the estuary and the habitat types. For example, habitat type sensitivity for the Cape's estuaries ranges from relatively sensitive seagrass beds to less sensitive mud flats.

Ecological impacts are structural or functional changes resulting from the interaction of exposure and sensitivity and represent the degree to which the estuary is affected. Eutrophication can decrease water clarity, induce hypoxia, and smother areas with organic matter that can degrade seagrass beds that provide habitat for shellfish, fish, and other organisms (Driscoll et al. 2003; Howes et al. 2003). Loss of seagrass habitat (i.e., eelgrass, *Zostera marina* L.) is often used as a measurement of ecological impact in TMDLs for estuaries like those on Cape Cod because of the sensitivity to poor water clarity, which often results from eutrophication (Howes et al. 2003). Partly as a result of eutrophication, some estuaries on Cape Cod have lost most, if not all, of their historic seagrass coverage (Costello and Kenworthy 2011). Seagrass coverage is important because these systems stabilize sediment, and alter water flow, nutrient cycling, and food web structure which influence the physical, chemical, and biological environments in coastal systems (Orth et al. 2006). Ecological impacts need not be limited to habitat measures but might also encompass other outcomes of the ecological system's functioning that ultimately relate to ecosystem services affecting the social system, such as the frequency and magnitude of algal blooms or declining species richness.

There is an increasing body of vulnerability research that extends beyond traditional risk assessment (e.g., Turner et al. 2003; Kasperson et al. 1988) to identify ways in which social and ecological systems may be impacted differently depending on recovery potential (ecological) or adaptive capacity (social). In our framework, the *recovery potential* of the ecological system is the ability of the system to regain its structure and/or functional condition over time, given a reduction in exposure. Visually, recovery potential is the ease at which the system returns to the dynamic equilibrium resulting in high levels of ecosystem services (Figure 1c). The recovery potential of a specific Cape Cod estuary might be affected by its volume and the water residence time, benthic stocks of existing nitrogen, or the abundance of species (such as seagrasses or shellfish) that might be necessary for the estuary to return to a condition in which it can sustainably deliver high levels of ecosystem services. In other cases, the system's recovery potential may be minimal if important structural and/or functional thresholds are crossed (e.g., after the loss of a keystone species). Notably, not all ecological perturbations are reversible (Palumbi, McLeod, and Grünbaum 2008).

Typically, recovery potential refers to a pulse-response relationship more appropriate to an acute hazard. This complicates the concepts of recovery potential and sensitivity given the chronic nature of the nitrogen exposure, as there is not a clean "before and after" in relation to the exposure. Recovery potential is similar to the sensitivity of the system, but we make a distinction between the effect of a constant or increasing exposure and the effect of a decrease in exposure. This distinction between sensitivity and recovery potential is a result of hysteresis, where the response of a system is dependent on the history of exposure, making positive or negative changes in exposure result in asymmetric system responses (Harris 1999). For the Cape, the chronic nitrogen exposure has led to elevated concentrations of nutrients in the benthic sediments, decreased benthic species abundance and diversity, and changes in water clarity, which affect the state of the system as well as both its recovery potential and sensitivity.

Ecological production functions are used to describe the change in the provision of ecosystem services for a given level of ecological impact. The functions connect ecosystem structure and function to FEGS endpoints, those directly used to yield human well-being (Landers and Nahlik 2013; Johnston and Russell 2011). Therefore, the quantity and quality of inputs from the ecological system received by the social system are delivered through final *ecosystem services*. Although they are not necessary in all cases to conceptualize benefits from nature, the FEGS definitions help to separate the quantifiable but intermediate services of nature from those that are directly valued by people. Recreational opportunities are among the most salient and valuable benefits provided to residents and visitors of the Cape by the ecosystem services of the estuaries. These recreational opportunities may be reduced or rendered impossible when water quality, as well as the shoreline and bottom conditions, are degraded.

The *sensitivity* of the social system is the susceptibility to harm of the community or individuals from changes in ecosystem services. Environmental economists might quantify sensitivity by relating changes in aggregate market and non-market values to changes in the ecosystem services in question (Tietenberg and Lewis 2010). A number of factors affect this relationship, such as the scarcity of recreational opportunities, social preference, or the community demographics (e.g., Smith et al. 2016). For example, a Cape Cod community may be more sensitive if most of its members have chosen to live in the area because of its water recreation opportunities. The community may also be sensitive to market impacts from changes in ecosystem services based on its level of dependence on tourism revenue.

The combination of the ecosystem services provided through water quality improvements or degradation and the sensitivity of the social system to changes in those services determines the *social impact*. This impact can be measured through losses or gains of recreational opportunities, changes to sense of place, economic activity including tourism revenue, and other socio-economic indicators. Excess algal growth leads to reduced aesthetic quality of coastal areas and may affect the quality or availability of recreational opportunities for the adjacent communities. Large mats of sea lettuce (*Ulva lactuca* L.) and other macroalgae can cover beaches and shellfishing areas, which inhibits water-based recreation (see e.g., Spillane 2016). There is evidence that eutrophication has led to decreased residential property values on the Cape (Ramachandran 2015), but the broader social impacts, such as those related to recreation, are still being identified.

The *adaptive capacity* of the social system is its individuals' and institutions' abilities to respond to and moderate negative social impacts from the chronic stressors by capitalizing upon opportunities and creativity and coping with any remaining consequences (modified from Gupta et al. 2010). The adaptive capacity for Cape communities is determined by their social, political and regulatory structure, budgetary constraints, human capital and the available technologies. In this framework, adaptive capacity leads to the ability to reduce nitrogen loading in the system through *policies and interventions*. The costs of the alternative approaches to nitrogen abatement vary by technology, as do the impacts and intersections with the natural system. Cape Cod's seasonal population spikes and relatively low-density development makes sewering less economically feasible than in more urbanized settings (Cape Cod Commission 2013). The efficacy and costs of alternatives to sewering are less certain, but potential cost savings and ancillary environmental benefits remain enticing. However, estimates of their efficacy, costs, and time until impact at the estuary vary widely. These alternative technologies also have different impacts on segments of the population on the Cape and varying levels of social acceptance.

While we focus on the internal dynamics of the coastal social-ecological system in this framework, we acknowledge the presence of *external forces, external impacts and co-benefits*. This social-ecological system does not exist alone, but instead, is embedded in multiple levels of systems (Holling 2001). External forces, whether those be larger environmental forces (e.g., climate change) or regional economic trends (e.g., interest rates), influence the progression of the social-ecological system under consideration. For example, atmospheric deposition of nitrogen certainly affects the system (Valiela et al. 2016), but decisions for its control are not entirely managed by communities in the system. The system may also produce co-benefits, such as carbon sequestration, or other negative impacts, like debt burdens, to other systems or at other scales.

Discussion

The chronic nature of the nutrient enrichment problem on the Cape led to a number of insights important to understanding and managing the resilience of a social-ecological system. Nitrogen over-enrichment erodes the resilience of an estuary, triggering effects throughout the system. Relative to acute events, the increased length of time a social system has to respond to slow-impact stressors provides increased opportunities to modify behaviors, policies, and practices to address or mitigate the impacts (Cutter et al. 2008). Despite having sufficient time, social systems often do not effectively recognize and address chronic stressors leading to water quality degradation. On Cape Cod, nitrogen loading into many of its estuaries has not decreased despite regional planning efforts to address the issue dating back to the 1970s (Cape Cod Commission 2015; Cape Cod Planning and Economic Development Commission 1978). Put in the context of our resilience framework, the primary feedback mechanism, from changes in ecosystem services through implementing policies and interventions, has been weak or slow. We discuss below why this might be the case given the structure of the social-ecological system on the Cape. Targeted and integrated research designed through this framework could enhance the resilience of the Cape social-ecological system by clarifying and strengthening the elements in the primary feedback mechanism of the system by filling knowledge gaps needed to inform ongoing management decisions.

There are many parts of the Cape's social-ecological system feedback loop that could be strengthened or better understood. Research directed at reducing the uncertainty in the sensitivity of the communities to changes in ecosystem services is needed to quantify the benefits to human well-being of investment in recovery of the estuaries. Without this information, the formidable costs of improving water quality lack defensible counterbalances in public debate as to how and when to intervene. Research is needed to understand the efficacy of nitrogen mitigation strategies, in addition to the social factors that lead a community to choose to implement a particular nitrogen mitigating policy or action.

Uncertainty in the ability of certain policies and interventions to reduce nitrogen loading constrains their possible use. As a result of this limitation, research is being conducted on the effectiveness of a number of approaches. These include determining the efficacy of certain ecological restoration efforts for reducing nitrogen loads and improving water quality. One of these efforts is the conversion of a cranberry farm to a freshwater wetland. In addition, we are installing and monitoring a living shoreline (constructed from coir logs, sand, plants and mussels) to protect salt marsh habitat. A third effort is examining the viability of home septic-scale permeable reactive barriers that could be subject to saltwater intrusion. The results of these studies will provide communities and decision makers with valuable information on the effectiveness of these approaches for changing the exposure, in this case removing or sequestering nitrogen. This information can be used by managers to develop remediation strategies tailored for each watershed and community.

Compounding the uncertainty in the policies and interventions, is uncertainty in the state, functioning and trajectory of the ecological system. In response, we are investigating monitoring approaches to provide observable measures of changes in exposure and ecological impact, and possibly track recovery. We are investigating the use of stable isotope analyses to evaluate the impact of nitrogen intervention strategies in affecting the ecological impacts in the estuary itself and not just at the various project sites.

The functioning of the social components of the system (*sensitivity*, *social impact* and *adaptive capacity*) are not well-understood. The Cape's social system consists of year-round residents, seasonal residents and tourists. Sensitivity to changes in the provision of ecosystem services from the coastal estuaries likely differs by the type of beneficiary or community as they are more or less dependent on these ecosystem services or more or less temporary to the region. We are conducting research to quantify the demand for ecosystem services supporting recreation at a community scale through social science and environmental economic valuation methods using focus groups, on-site counts, and spatial modeling.

Across the Cape, the burden of the costs and responsibility for reducing the nitrogen exposure, as well as benefits from improvements, fall unequally across communities. Because of the breadth of some watersheds, there are communities who may be contributing nitrogen to an estuary but are miles from the coastline. These asymmetries make self-organization of communities or stakeholders, an important element of adaptive capacity, more difficult (Folke et al. 2002). Structured approaches to decision making allow scientists and decision makers to investigate problems where ecological and social information must be modeled and integrated to compare management decisions (Gregory et al. 2012). We are working with local watershed managers in a degraded watershed on the Cape to illustrate this approach and incorporate ecosystem services as a water quality management objective (Martin et al. 2018). We are also conducting semi-structured interviews with managers on the Cape to identify barriers and opportunities to the use of alternative technologies beyond just financial costs and efficiency in nitrogen reduction.

The chronic nature of the exposure further complicates management. This includes an extended history of nitrogen already in the estuary, the time it will take policies and intervention to affect the loading, and the long time it may take the socio-political system to identify social and ecological impacts. When these factors are combined with social time discounting (EPA 2010; Frederick, Loewenstein, and O'donoghue 2002), the strength of the translation from ecological impact to exposure-reducing actions is weakened. In response, we are explicitly modeling the dynamics of the delivery of nutrients to the estuary through groundwater, comparing various policies and interventions in terms of their time to impact. We seek to estimate efficient solutions through dynamic optimization methods for where, when, and how to intervene through the watershed and in the estuary itself.

Conclusion

Nitrogen pollution and other water quality issues are complex problems. Tackling these problems requires understanding both the ecological system and social system, as well as the many connections between these systems since the structure and function of one depends on the other. Our framework was developed to inform interdisciplinary research on Cape Cod related to estuarine nutrient loading, but it is intended to be flexible to other systems with chronic water quality issues. The Cape is not unique in its coastal eutrophication issues, even regionally in New England. Efforts are ongoing in Narragansett Bay, Long Island Sound, and Boston Harbor to address similar problems.

Beyond coastal water quality issues, framing the research agenda in terms of ecosystem services, resilience and social-ecological systems concepts may be beneficial in generating future interdisciplinary research hypotheses and to inform long-term community planning decisions. This approach may be useful for application to other chronic stressors, such as coastal erosion, salt marsh degradation, ocean acidification, and sea-level rise. Research efforts should target resilience-limiting gaps in knowledge and reduce uncertainty in our understanding of key components of the system that inhibit effective management.

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References

Adger, W. N., T. P. Hughes, C. Folke, S. R. Carpenter, and J. Rockström. 2005. Social-ecological resilience to coastal disasters. *Science* 309 (5737):1036–9. doi:10.1126/science.1112122.

Berkes, F., and C. Folke, eds. 1998. *Linking social and ecological systems: Management practices and social mechanisms*. Cambridge, UK: Cambridge University Press.

Biggs, R., M. Schlüter, and M. L. Schoon, eds. 2015. *Principles for building resilience: Sustaining ecosystem services in social-ecological systems*. Cambridge, UK: Cambridge University Press.

Bricker, S. B., C. G. Clement, D. E. Pirhalla, S. P. Orlando, and D. R. G. Farrow. 1999. *National estuarine eutrophication assessment: Effects of nutrient enrichment in the nation's estuaries*, 71 pp. Silver Spring, MD: NOAA, National Ocean Service, Special Projects Office and the National Centers for Coastal Ocean Science.

Brookes, J. D., and C. C. Carey. 2011. Ecology. Resilience to blooms. *Science* 334 (6052):46–7. doi:10.1126/science.1207349.

Brose, D. A. 2015. *Developing a framework for measuring community resilience: Summary of a workshop*. Washington, DC: National Academies Press.

Cape Cod Commission. 2013. Regional wastewater management plan: Estimating cape-wide costs of wastewater infrastructure. http://www.capecodcommission.org/resources/RWMP/RWMP_costs_capewide.pdf (accessed March 30, 2017).

Cape Cod Commission. 2015. Cape Cod area wide water quality management plan update. http://www.capecodcommission.org/index.php?id=491 (accessed March 30, 2017).

Cape Cod Commission. 2017a. Draft 2017 implementation report. http://www.capecodcommission.org/index.php?id =625&maincatid=491 (accessed October 3, 2017).

Cape Cod Commission. 2017b. Technologies matrix. http://www.cch2o.org/Matrix/ (accessed February 14, 2017).

Cape Cod Planning and Economic Development Commission. 1978. Environmental Impact Statement and 208 Water Quality Management Plan for Cape Cod. Boston, MA: US Environmental Protection Agency.

Carpenter, S. R., and K. L. Cottingham. 1997. Resilience and restoration of lakes. *Conservation Ecology* 1 (1):2. doi:10.5751/ES-00020-010102.

Carpenter, S. R., and L. H. Gunderson. 2001. Coping with collapse: Ecological and social dynamics in ecosystem management. *BioScience* 51 (6):451–7. doi:10.1641/0006-3568(2001)051[0451:CWCEAS]2.0.CO;2.

Cimellaro, G. P. 2016. *C. 6 PEOPLES resilience framework in urban resilience for emergency response and recovery*, 109–37. Basel, Switzerland: Springer International Publishing.

Cinner, J. E., C. Huchery, E. S. Darling, A. T. Humphries, N. A. Graham, C. C. Hicks, N. Marshall, and T. R. McClanahan. 2013. Evaluating social and ecological vulnerability of coral reef fisheries to climate change. *PLoS One* 8 (9):e74321. doi:10.1371/journal.pone.0074321.

Collins, S. L., S. R. Carpenter, S. M. Swinton, D. E. Orenstein, D. L. Childers, T. L. Gragson, N. B. Grimm, J. M. Grove, S. L. Harlan, J. P. Kaye, A. K. Knapp, G. P. Kofinas, J. J. Magnuson, W. H. McDowell, J. M. Melack, L. A. Ogden, G. P. Robertson, M. D. Smith, and A. C. Whitmer. 2011. An integrated conceptual framework for long-term social–ecological research. *Frontiers in Ecology and the Environment* 9 (6):351–7. doi:10.1890/100068.

Costello, C. T., and W. J. Kenworthy. 2011. Twelve-year mapping and change analysis of eelgrass (*Zostera marina*) areal abundance in Massachusetts (USA) identifies statewide declines. *Estuaries and Coasts* 34 (2):232–42. doi:10.1007/s12237-010-9371-5.

Cottingham, K. L., and S. R. Carpenter. 1994. Predictive indices of ecosystem resilience in models of north temperate lakes. *Ecology* 75 (7):2127–38. doi:10.2307/1941616.

Cumming, G. S., G. Barnes, S. Perz, M. Schmink, K. E. Sieving, J. Southworth, M. Binford, R. D. Holt, C. Stickler, and T. Van Holt. 2005. An exploratory framework for the empirical measurement of resilience. *Ecosystems* 8 (8):975–87. doi:10.1007/s10021-005-0129-z.

Cutter, S. L. 2016. The landscape of disaster resilience indicators in the USA. *Natural Hazards* 80 (2):741–58. doi:10.1007/s11069-015-1993-2.

Cutter, S. L., L. Barnes, M. Berry, C. Burton, E. Evans, E. Tate, and J. Webb. 2008. A place-based model for understanding community resilience to natural disasters. *Global Environmental Change* 18 (4):598–606. doi:10.1016/j.gloenvcha.2008.07.013.

Doney, S. C. 2010. The growing human footprint on coastal and open-ocean biogeochemistry. *Science* 328 (5985):1512–6. doi:10.1126/science.1185198.

Driscoll, C. T., D. Whitall, J. Aber, E. Boyer, M. Castro, C. Cronan, C. L. Goodale, P. Groffman, C. Hopkinson, K. Lambert, and G. Lawrence. 2003. Nitrogen pollution in the northeastern United States: Sources, effects, and management options. *BioScience* 53 (4):357–74. doi:10.1641/0006-3568(2003)053[0357:NPITNU]2.0.CO;2.

Duh, J. D., V. Shandas, H. Chang, and L. A. George. 2008. Rates of urbanisation and the resiliency of air and water quality. *Science of the Total Environment* 400 (1–3):238–56. doi:10.1016/j.scitotenv.2008.05.002.

EPA. 2010. Guidelines for preparing economic analyses. 2010. https://www.epa.gov/environmental-economics/guidelines-preparing-economic-analyses (accessed March 3, 2017).

Folke, C., S. Carpenter, T. Elmqvist, L. Gunderson, C. S. Holling, and B. Walker. 2002. Resilience and sustainable development: Building adaptive capacity in a world of transformations. *AMBIO: A Journal of the Human Environment* 31 (5):437–40. doi:10.1579/0044-7447-31.5.437.

Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, and C. S. Holling. 2004. Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology, Evolution, and Systematics* 35 (1):557–81. doi:10.1146/annurev.ecolsys.35.021103.105711.

Frederick, S., G. Loewenstein, and T. O'donoghue. 2002. Time discounting and time preference: A critical review. *Journal of Economic Literature* 40 (2):351–401. doi:10.1257/002205102320161311.

Gregory, R., L. Failing, M. Harstone, G. Long, T. McDaniels, and D. Ohlson. 2012. *Structured decision making: A practical guide to environmental management choices*. West Sussex, United Kingdom: Wiley-Blackwell.

Gunderson, L., S. Carpenter, C. Folke, P. Olsson, and G. Peterson. 2006. Water RATs (resilience, adaptability, and transformability) in lake and wetland social-ecological systems. *Ecology and Society* 11 (1):16. doi:10.5751/ES-01556-110116.

Gupta, J., C. Termeer, J. Klostermann, S. Meijerink, M. van den Brink, P. Jong, S. Nooteboom, and E. Bergsma. 2010. The adaptive capacity wheel: A method to assess the inherent characteristics of institutions to enable the adaptive capacity of society. *Environmental Science & Policy* 13 (6):459–71. doi:10.1016/j.envsci.2010.05.006.

Halpern, B. S., S. Walbridge, K. A. Selkoe, C. V. Kappel, F. Micheli, C. D'Agrosa, J. F. Bruno, K. S. Casey, C. Ebert, H. E. Fox, R. Fujita, D. Heinemann, H. S. Lenihan, E. M. Madin, M. T. Perry, E. R. Selig, M. Spalding, R. Steneck, and R. Watson. 2008. A global map of human impact on marine ecosystems. *Science* 319 (5865):948–52. doi:10.1126/science.1149345.

Harris, G. P. 1999. Comparison of the biogeochemistry of Lakes and estuaries: Ecosystem processes, functional groups, hysteresis effects and interactions between macro-and microbiology. *Marine and Freshwater Research* 50 (8):791–811. doi:10.1071/MF99111.

Holling, C. S. 1973. Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics* 4 (1):1–23. doi:10.1146/annurev.es.04.110173.000245.

Holling, C. S. 2001. Understanding the complexity of economic, ecological, and social systems. *Ecosystems* 4 (5):390–405. doi:10.1007/s10021-001-0101-5.

Howes, B. L., R. I. Samimy, and B. Dudley. 2003. Massachusetts Estuaries Project. Site-specific nitrogen thresholds for southeastern Massachusetts embayments: Critical indicators. http://www.oceanscience.net/estuaries/documents.htm (accessed March 3, 2017).

Hughes, T. P., A. H. Baird, D. R. Bellwood, M. Card, S. R. Connolly, C. Folke, R. Grosberg, O. Hoegh-Guldberg, J. B. C. Jackson, J. Kleypas, J. M. Lough, P. Marshall, M. Nyström, S. R. Palumbi, J. M. Pandolfi, B. Rosen, and J. Roughgarden. 2003. Climate change, human impacts, and the resilience of coral reefs. *Science* 301 (5635):929–33. doi:10.1126/science.1085046.

Johnston, R. J., and M. Russell. 2011. An operational structure for clarity in ecosystem service values. *Ecological Economics* 70 (12):2243–9. doi:10.1016/j.ecolecon.2011.07.003.

Kasperson, R. E., O. Renn, P. Slovic, H. S. Brown, J. Emel, R. Goble, J. X. Kasperson, and S. Ratick. 1988. The social amplification of risk: A conceptual framework. *Risk Analysis* 8 (2):177–87. doi:10.1111/j.1539-6924.1988.tb01168.x.

Landers, D. H., and A. M. Nahlik. 2013. Final ecosystem goods and services classification system (FEGS-CS). Report No. EPA/600/R-13/ORD-004914. United States Environmental Protection Agency, Washington, D.C.

Marshall, N. A., P. A. Marshall, J. Tamelander, D. Obura, D. Malleret-King, and J. E. Cinner. 2010. A framework for social adaptation to climate change: Sustain tropical coastal communities and industries. IUCN Report. 44 pp. IUCN, Gland, Switzerland.

Martin, D. M., A. N. Piscopo, M. M. Chintala, T. R. Gleason, and W. Berry. 2018. Developing qualitative ecosystem service relationships with the driver-pressure-state-impact-response framework: A case study on Cape Cod, Massachusetts. *Ecological Indicators* 84:404–15. doi:10.1016/j.ecolind.2017.08.047.

Milman, A., and A. Short. 2008. Incorporating resilience into sustainability indicators: An example for the urban water sector. *Global Environmental Change* 18 (4):758–67. doi:10.1016/j.gloenvcha.2008.08.002.

Nixon, S. W. 1992. Quantifying the relationship between nitrogen input and the productivity of marine ecosystems. In Proceedings of Advanced Marine Technology Conference, Tokyo, Japan, No. 5, 57–83.

Nyström, M., C. Folke, and F. Moberg. 2000. Coral reef disturbance and resilience in a human-dominated environment. *Trends in Ecology and Evolution (Amsterdam)* 15 (10):413–7. doi:10.1016/S0169-5347(00)01948-0.

Orth, R. J., T. J. Carruthers, W. C. Dennison, C. M. Duarte, J. W. Fourqurean, K. L. Heck, Jr., A. R. Hughes, G. A. Kendrick, W. J. Kenworthy, S. Olyarnik, and F. T. Short. 2006. A global crisis for seagrass ecosystems. *Bioscience* 56 (12):987–96. doi:10.1641/0006-3568(2006)56[987:AGCFSE]2.0.CO;2.

Palumbi, S. R., K. L. McLeod, and D. Grünbaum. 2008. Ecosystems in action: Lessons from marine ecology about recovery, resistance, and reversibility. *BioScience* 58 (1):33–42. doi:10.1641/B580108.

Proença, P., and J. Fernández-Manjarrés. 2015. Regime shifts in social-ecological systems. Action Bioscience. http://www.actionbioscience.org/environment/proenca_fernandezmanjarres.html#primer (accessed March 3, 2017).

Ramachandran, M. 2015. Validating spatial hedonic modeling with a behavioral approach: Measuring the impact of water quality degradation on coastal housing markets. No 205664. Paper presented at 2015 AAEA & WAEA Joint Annual Meeting, Agricultural and Applied Economics Association, San Francisco, CA, July 26–28.

Scheffer, M., S. Carpenter, J. A. Foley, C. Folke, and B. Walker. 2001. Catastrophic shifts in ecosystems. *Nature* 413 (6856):591–6. doi:10.1038/35098000.

Smith, J. W., E. Seekamp, A. McCreary, M. Davenport, M. Kanazawa, K. Holmberg, B. Wilson, and J. Nieber. 2016. Shifting demand for winter outdoor recreation along the North shore of lake superior under variable rates of climate change: A finite-mixture modeling approach. *Ecological Economics* 123:1–13. doi:10.1016/j.ecolecon.2015.12.010.

Spillane, G. 2016. Major algae bloom outbreak in Cotuit, Osterville. Cape Cod Times, Hyannis, MA, August 16.

Tietenberg, T. H., and L. Lewis. 2010. *Environmental economics and policy*. New York, NY: Pearson.

Tomasky, G., J. Barak, I. Valiela, P. Behr, L. Soucy, and K. Foreman. 1999. Nutrient limitation of phytoplankton growth in Waquoit Bay, Massachusetts, USA: A nutrient enrichment study. *Aquatic Ecology* 33:147–55. doi:10.1023/A:1009912430833.

Turner, B. L., R. E. Kasperson, P. A. Matson, J. J. McCarthy, R. W. Corell, L. Christensen, N. Eckley, J. X. Kasperson, A. Luers, M. L. Martello, C. Polsky, A. Pulsipher, and A. Schiller. 2003. A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences of the United States of America* 100 (14):8074–9. doi:10.1073/pnas.1231335100.

Underdal, A. 2010. Complexity and challenges of long-term environmental governance. *Global Environmental Change* 20 (3):386–93. doi:10.1016/j.gloenvcha.2010.02.005.

Unsworth, R. K., C. J. Collier, M. Waycott, L. J. Mckenzie, and L. C. Cullen-Unsworth. 2015. A framework for the resilience of seagrass ecosystems. *Marine Pollution Bulletin* 100 (1):34–46. doi:10.1016/j.marpolbul.2015.08.016.

Valiela, I., J. Costa, K. Foreman, J. M. Teal, B. Howes, and D. Aubrey. 1990. Transport of groundwater-borne nutrients from watersheds and their effects on coastal waters. *Biogeochemistry* 10 (3):177–97. doi:10.1007/BF00003143.

Valiela, I., C. Owens, E. Elmstrom, and J. Lloret. 2016. Eutrophication of Cape Cod estuaries: Effect of decadal changes in global-driven atmospheric and local-scale wastewater nutrient loads. *Marine Pollution Bulletin* 110 (1):309–15. doi:10.1016/j.marpolbul.2016.06.047.

Van Oudenhoven, F. J., D. Mijatović, and P. B. Eyzaguirre. 2011. Social-ecological indicators of resilience in agrarian and natural landscapes. *Management of Environmental Quality: An International Journal* 22 (2):154–73. doi:10.1108/14777831111113356.

Wainger, L., and M. Mazzotta. 2011. Realizing the potential of ecosystem services: A framework for relating ecological changes to economic benefits. *Environmental Management* 48 (4):710. doi:10.1007/s00267-011-9726-0.

Walter, D. A., J. P. Masterson, and K. M. Hess. 2005. *Ground-water recharge areas and travel-times to pumped wells, ponds, streams, and coastal water bodies, Cape Cod, Massachusetts*. Reston, VA: US Geological Survey.

Yoskowitz, D., and M. Russell. 2015. Human dimensions of our estuaries and coasts. *Estuaries and Coasts* 38 (S1):1–8. doi:10.1007/s12237-014-9926-y.