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A review of coastal management approaches to support the integration of ecological and human community planning for climate change

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Abstract

The resilience of socio-ecological systems to sea level rise, storms and flooding can be enhanced when coastal habitats are used as natural infrastructure. Grey infrastructure has long been used for coastal flood protection but can lead to unintended negative impacts. Natural infrastructure often provides similar services as well as added benefits that support short- and long-term biological, cultural, social, and economic goals. While natural infrastructure is becoming more widespread in practice, it often represents a relatively small fraction within portfolios of coastal risk-reducing strategies compared to more traditional grey infrastructure. This study provides a comprehensive review of how natural infrastructure is being used along the United States Atlantic, Gulf of Mexico, and Caribbean coasts related to four habitats – tidal marshes, beaches and barrier islands, mangroves, and biogenic reefs. We compare information on the benefits, opportunities and challenges of implementing natural, grey and hybrid infrastructure in the coastal zone. In addition, we present a suite of actions to increase information and reduce uncertainty so that coastal mangers and planners are aware of the full suite of options for restoration, conservation and planning that maximize ecosystem services over short- and long-term planning horizons.

Keywords Natural infrastructure · Restoration · Thresholds · Sea level rise · Coastal storms · Ecosystem services

Introduction

Human and natural communities located in the coastal zone are increasingly threatened by climate impacts (e.g., sea level rise (SLR), flooding from coastal storms and coastal erosion) and anthropogenic stressors (e.g., pollution, land use change and development) (e.g., Donnelly and Bertness 2001; Feagin et al. 2005; Erwin et al. 2006; Defeo et al. 2009; Shepard et al. 2012; Fagherazzi et al. 2013; Valle-Levinson et al. 2017; Dahl et al. 2017). In recent years, coastal systems along the United States Atlantic, Gulf of Mexico, and Caribbean coasts have also experienced a number of extreme events (e.g., Hurricanes Katrina, Rita, Ike, Gustav, Sandy, Harvey, Irma, Maria) and accidents (e.g., *Deepwater Horizon* oil spill). The combined effects of these gradual and acute threats requires innovative, holistic and collaborative approaches to reduce risk (e.g., Adger et al. 2005; NOAA 2015; Wamsler et al. 2016). This includes coastal adaptation strategies that consider short- and long-term climate scenarios, uncertainty, cost-benefit analyses of competing actions, as well as the incorporation of nature and natural elements into shoreline management systems (Stein et al. 2013; RAE 2015).

Inherent to coastal adaptation is the concept of resilience, which is the ability of socio-ecological systems to absorb and recover from disturbances, while retaining or even regaining essential structures, processes or functions (Adger et al. 2005; Folke 2006; Cutter et al. 2008; Fisichelli et al. 2016). Managing for resilience can take several forms, including: 1) resisting change through restoration and maintenance of

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current conditions, 2) accommodating some level of change after a disturbance, but generally returning to a previous state, or 3) facilitating change either through active management towards a desired new state (e.g., reorganization) or passively allowing for autonomous change (Fisichelli et al. 2016). Natural infrastructure, including natural habitats and features designed to mimic natural processes, can serve as an alternative management approach to traditional grey infrastructure for risk reduction and may provide added benefits to socio-ecological systems (e.g., Arkema et al. 2013; Reguero et al. 2018). These benefits can be characterized as supporting, regulating, culturally sustaining, and provisioning ecosystem services and include enhanced erosion control, recreation and habitat preservation, among others (MEA 2005; Gedan et al. 2010; NOAA 2010; Scyphers et al. 2011; Grabowski et al. 2012; Bridges et al. 2015). While natural infrastructure is becoming more widespread in practice, it often represents a relatively small fraction of a community's portfolio of coastal risk-reducing strategies when compared to more traditional grey infrastructure (Temmerman et al. 2013; Sutton-Grier et al. 2015; Small-Lorenz et al. 2016; Wamsler et al. 2016; Bilkovic et al. 2016).

The goal of this study is to increase awareness of how natural infrastructure is being used in the coastal zone to enhance socio-ecological resilience to natural and anthropogenic stressors. We assessed the benefits, opportunities and best practices of using four costal habitats, 1) tidal marshes, 2) beaches and barrier islands, 3) biogenic reefs, and 4) mangroves, as natural infrastructure across the U.S. Atlantic, Gulf of Mexico, and Caribbean coasts. In addition, we provide an overview of remaining challenges and information needs that impede systematic consideration of natural infrastructure in coastal planning and management.

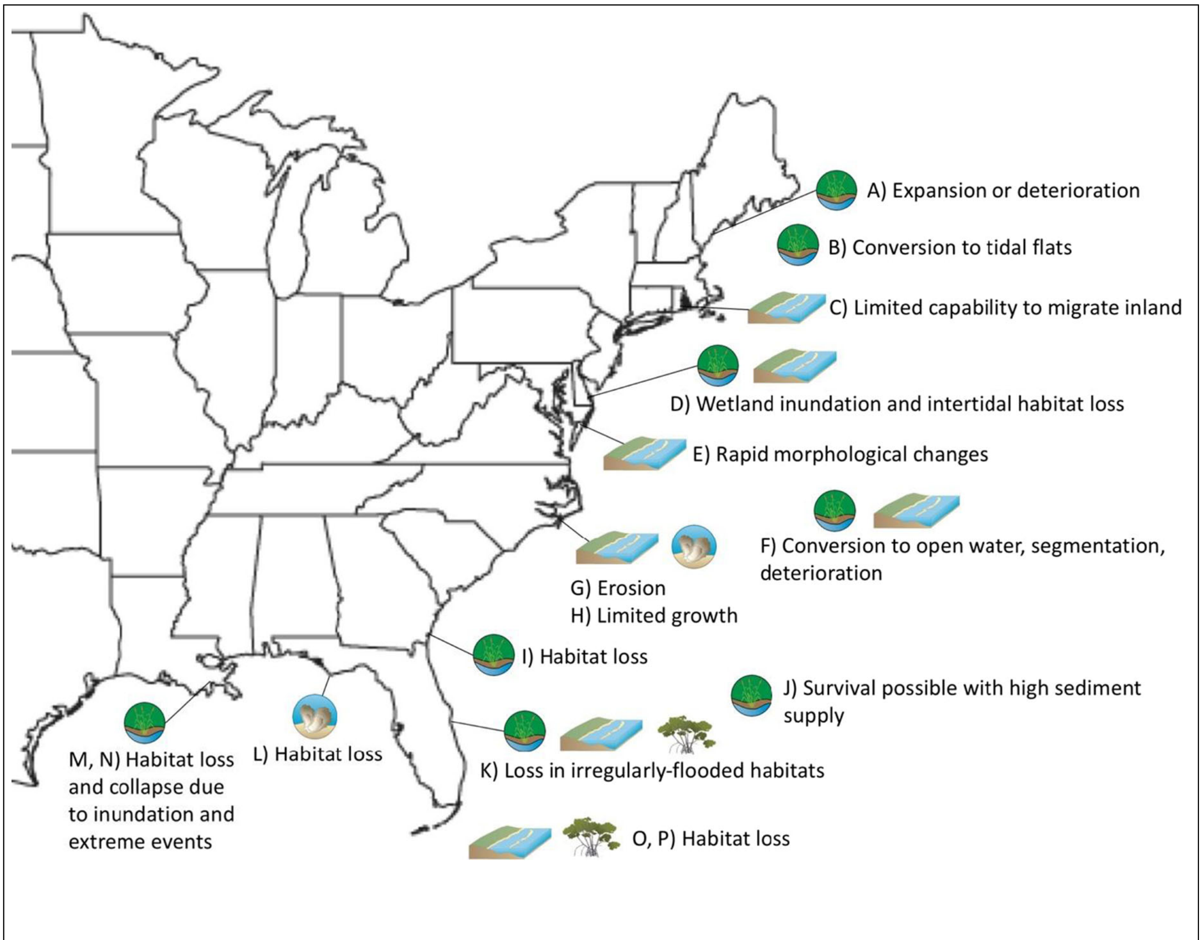
The impacts and potential responses of coastal habitats to sea level rise, storms and other stressors

Tidal marshes, beaches and barrier islands, biogenic reefs, and mangroves provide critical nesting, foraging and resting habitat for many fish and wildlife species of high conservation concern, as well as essential nursery and refuge habitat for commercially and recreationally important fishes and invertebrates (NRC 2007; Gedan et al. 2010). These four habitats also benefit coastal communities by providing risk reduction through the attenuation or dissipation of wave energy, breaking of offshore waves, slowing of inland water transfer (NRC 2007; Costanza et al. 2008; Gedan et al. 2010), and sediment stabilization (NRC 2007; Gedan et al. 2010; Scyphers et al. 2011; Gittman et al. 2014; La Peyre et al. 2015). The resilience of these four habitats to rising sea levels, coastal flooding, extreme storm events, and other stressors over the near and long-term depends largely on the exposure to a threat (e.g., rate of local SLR) and sensitivity to a threat based on the surrounding local conditions (e.g., availability of suitable adjacent habitat) to support dynamic response to stressors.

The interactive effects of multiple stressors, such as extreme events and SLR, may push some coastal ecosystems to undergo sudden, rapid and irreversible shifts that result in abrupt or nonlinear changes in an ecosystem quality, property or phenomenon, known as a threshold (CCSP 2009). Quantitative thresholds are important indicators of habitat changes or landscape responses to stressors like SLR and storm surge that could lead to a reduction in a valued resource and related ecosystem services (Powell et al. 2017). A synthesis of existing information on quantitative thresholds and observed or modeled responses to SLR for tidal marshes, beaches and barrier islands, biogenic reefs, and mangroves along the U.S. Atlantic, Gulf, and Caribbean coasts found preliminary information on salt marshes across the geography (Table 1). However, threshold data were scarce for biogenic reefs, mangroves, and beach and barrier island systems, specifically along the northern Gulf of Mexico. Overall, $\geq$ 50 cm of SLR by 2100 is expected to result in widespread coastal habitat losses along the Atlantic, Gulf, and Caribbean coasts, although losses may vary substantially based on local factors, such as nearshore bathymetry, exposure to severe storms, wave action, and rates of surface elevation change (Fagherazzi et al. 2013; Raposa et al. 2016; Ganju et al. 2017). Some wetlands were predicted to persist in the near term under moderate rates of global SLR (e.g., ~100 cm by 2100) through feedback mechanisms, such as submergence-accretion (wetland inundation with sediment-laden water) and increased plant productivity with submergence (Gedan et al. 2010).

Moderate to high rates of projected SLR (roughly 50–80 cm by 2100) have the potential to substantially impact coastal habitats and degrade, reduce or remove associated ecosystem services (Field 1995; Erwin et al. 2006; Bin et al. 2007; Craft et al. 2009; Melillo et al. 2014). For instance, a 50 cm rise in sea levels by 2100 along the Georgia coast is predicted to convert salt marsh areas to tidal flats and open water, with a concomitant reduction in their productivity and nitrogen sequestration abilities (Craft et al. 2009). Several modeling studies suggest marshes can accrete enough sediment or respond dynamically and keep pace with low to moderate rates of SLR (Lentz et al. 2016; Kirwan et al. 2016). However, empirical studies have shown that, in many places, marsh (Craft et al. 2009; Raposa et al. 2015; Armitage et al. 2015; Watson et al. 2015) and mangrove accretion (Gilman et al. 2008) are not actually keeping pace with current rates of SLR. In South Carolina, a parabolic relationship was demonstrated between inundation and primary production of smooth cordgrass (*Spartina alterniflora*), suggesting that near-term stability of intertidal salt marsh in response to local SLR depended on marsh elevation (Morris et al. 2002). For oyster reefs, vertical growth on unharvested oyster reefs is generally

Table 1 Synthesis of responses and quantitative tolerance thresholds related to amounts and rates of sea level rise along the Atlantic, Gulf, and Caribbean coasts for four habitat types: tidal marshes (TM,), beaches/barrier islands (BB,), oyster reefs (OR,), and mangroves (M,). The top figure shows locations where habitat responses and consequences to sea level rise have been observed or modeled across the geography; corresponding details are included in the table below. Icons were obtained from the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/)



	Location	Habitat Type				Projected Response to Sea Level Rise	Reference
		TM	BB	M	OR		
A	Wells, Maine	X				SLR of 50 cm over the next 100 years at current accretion rates led to marsh expansion at 1.14% annually by accreting and growing upwards or expanding laterally; SLR of 100 cm or more in the next 100 years led to marsh deterioration at 0.5% annually.	Torio and Chmura 2013
B	Southern New England and Long Island	X				Accelerating rates of relative SLR of > 0.2 cm per year, combined with suspended sediment concentrations below 2 mg per liter (stable salt marshes need higher suspended sediment concentrations), will convert salt marsh to tidal flats.	Watson et al. 2014
C	Rhode Island		X			Dynamic shorebird migration models show shorebird beach habitat migrated inland, with development beginning to block habitat migration under a SLR scenario of 50 cm by 2100.	Sims et al. 2013

Table 1 (continued)

D	Delaware Bay	X	X			(1) Over 95% of wetlands were inundated relative to current mean higher high water with a projected SLR of 50 cm by 2100, and 100% were inundated with a SLR of 100 cm by 2100, regardless of land conservation investments. (2) A 34 cm global SLR by 2100 (based on global temperature increases of 2°C) predicted a 57% loss of intertidal shorebird feeding habitat, while a 77 cm SLR by 2050 (based on global temperature increases of 4.7°C) led to 43% loss but could increase 20% by 2100 if the coastline migrates inland and dry land converts to intertidal.	(1) Shriver and Wiest 2013 (2) Galbraith et al. 2002
E	Assateague Island, Maryland and Virginia		X			A 20th century SLR rate with a 0.2 cm per year acceleration, 0.7 cm per year acceleration, and a 200 cm SLR rate over the next few hundred years is as likely as not, very likely, and virtually certain, respectively, to lead to a geomorphic threshold that results in rapid morphological changes in these barrier systems.	Gutierrez et al. 2007
F	Mid-Atlantic Region	X	X			Wetlands able to keep pace with 20th century rates of SLR could persist under a 0.2 cm per year acceleration of SLR, but only under optimal hydrology and sediment supply conditions. Wetlands would surpass thresholds and segment or disintegrate given 0.7 cm per year acceleration of SLR by 2100, with localized exceptions possible.	Titus et al. 2009
G	North Carolina		X			SLR scenarios of 11-21 cm by 2030 projected increases in erosion of 10%-30%, and SLR scenarios of 26-81 cm by 2080 projected increases in coastal erosion of 20%-60% for 17 recreational beaches, assuming a constant coast-wide rate of erosion, no barrier island migration, and no beach nourishment.	Bin et al. 2007
H	Rachel Carson component of the North Carolina National Estuarine Research Reserve				X	Greatest oyster reef growth rates occur between 20% and 40% exposure (emergence during the tidal cycle), with zero-growth boundaries occurring at 10% (coinciding with mean low water) and 55% exposures (growth ceiling). At current SLR (~0.3 cm per year), a critical-exposure boundary of 12% represents a depth where rates of reef growth and SLR are equal. At a SLR of 0.5 cm per year, substrates below 15% exposure are unsuitable for intertidal oyster reef habitat.	Ridge et al. 2015
I	Georgia coast	X				A SLR scenario of 80 cm by 2100 led to declines of 45% for salt marsh, 39% for tidal freshwater, and 1% for tidal brackish marsh areas (which is also likely for the entire southeast U.S. coast). A SLR scenario of 50 cm by 2100 caused an overall 20% reduction in salt marsh.	Craft et al. 2009

Table 1 (continued)

J	Southeast coast	X				In areas of high sediment supply, marshes dominated by *Spartina alterniflora* could survive relative SLR rates up to 1.25 cm per year.	Morris et al. 2002
K	Merritt Island National Wildlife Refuge, Florida	X	X	X		A global eustatic SLR of 100 cm (200 cm) by 2100 resulted in an 82% (92%) reduction in irregularly-flooded marsh habitat, 39% (83%) loss of mangrove habitat, and 47% (52%) loss of estuarine beach habitat.	USFWS 2011
L	Apalachicola Bay National Estuarine Research Reserve, Florida				X	Average oyster shell length and sedimentation peaked at 95% time inundated (submerged), which suggests 5% exposure time, while recruitment peaked at 80% time inundated (submerged), or 20% exposure rate.	Solomon et al. 2014
M	Mississippi Delta					(1) Microtidal marshes (<50 cm in Louisiana deltaic area) cannot accommodate a sharp and sustained increase in SLR, rates no more than 1 cm per year, and (2) are already experiencing high rates of wetland loss, which is accelerated by hurricanes.	(1) Kearney and Turner 2016 (2) Couvillion et al. 2011
N	Coastal Louisiana	X				Inundation depth thresholds for potential marsh collapse, as referenced to cm below mean low water are: 31-36 cm for intermediate marsh; 20-26 cm for brackish marsh; and 17-24 cm for saline marsh.	Couvillion and Beck 2013
O	Caribbean Islands		X			Up to 38% of total current beach could be lost with a global SLR of 50 cm by 2100, with low narrow beaches most vulnerable.	IPCC 2007
P	Global			X		(1) Mangroves on low limestone islands keep pace with 8-9 cm SLR per 100 years and are under stress at 9-12 cm per 100 years. (2) Extrapolating from results in American Samoa, local rates of SLR could account for 10%-20% of total future estimated losses of mangrove areas within the region.	(1) Field 1995 (2) Gilman et al. 2008

This synthesis is based on a review of the literature using Web of Science and google scholar with consistent search terms that combined the habitat name and "threshold" with the search terms "sea level rise" and "storms". Searches were conducted between February and August 2016

greater than predicted rates of SLR (Grabowski et al. 2012); however, intertidal oyster reef survival requires inland migration or juvenile recruitment to raise reef elevation and maximize recruitment, growth and survival relative to SLR (Solomon et al. 2014).

The wide range of studies that have assessed SLR impacts to Atlantic, Gulf, and Caribbean coastal habitats (Table 1) provide a starting point for understanding where and when thresholds may be crossed. These data combined with model outputs that identify where dynamic response (Lentz et al. 2016) or inland migration (Enwright et al. 2015) is most likely can be used to support effective adaptation and resilience actions, such as conserving or restoring viable inland habitats. However, habitat responses are complicated and decisions of which habitat to actively maintain or manage towards transition may not always be straight-forward due to complicated ecosystem interactions. For example, along the Texas coast, marsh areas are decreasing in size in response to local rates of SLR, while mangrove forests are expanding in response to rising winter temperature minima and leading to displacement of salt marshes in some areas (Armitage et al. 2015). While expansion may help to increase the overall extent of mangrove habitat, low island mangroves, which are functionally linked to adjacent coral reefs and experiencing simultaneous decreases in productivity, may suffer from lower sedimentation rates and increased susceptibility to SLR and storms (Gilman et al. 2008). Impediments posed by natural or human features of the surrounding landscape are additional challenges to decision-making. For example, under moderate to high scenarios of SLR, several studies (Table 1) show that habitats can persist by migrating upslope, unless hard coastline features (e.g., bedrock coast), development (e.g., Feagin et al. 2005) or steep slopes block or inhibit habitat movement inland (Lentz et al. 2016). Restricted movement of beaches within narrow zones also has the potential to alter habitat characteristics and interfere with ecological functions that provide protective services to the coast from wave energy, tides and winds (Griggs 2005; NRC 2007; Titus et al. 2009). Consequently, migration corridor planning is especially important in urbanized and high-elevation coastal areas to increase ecosystem connectivity and improve wetland migration (Enwright et al. 2015).

Summary of ecological and human community benefits of management approaches using natural infrastructure

Natural infrastructure is being successfully implemented as part of a suite of coastal adaptation actions along the U.S. Atlantic, Gulf of Mexico, and Caribbean coasts to enhance the resilience of socio-ecological communities to the impacts of SLR and storms (Table 2). The U.S. Army Corps of Engineers (USACE) previously synthesized data on the benefits derived from certain coastal habitats, as well as structural and non-structural coastal risk reduction strategies (USACE 2013). We used the USACE (2013) report as a baseline of information and expanded on its findings through an updated review of the peer-reviewed and grey literature. Our review aimed to provide a more comprehensive treatment of the range of management approaches that incorporate natural infrastructure and derived socio-ecological benefits (i.e., ecosystem services) related to tidal marshes, beaches and barrier islands, biogenic reefs, and mangroves. The socio-ecological benefits offered by these four habitats are organized into six management categories, including 1) restoration, 2) landscape conservation design, 3) living shorelines, 4) facilitated relocation, 5) open space preservation, and 6) land use planning (Table 2).

The management options described in Table 2 provide a range of ecosystem services that enhance resilience of coastal systems to gradual (e.g., climate change) and episodic (e.g., major storms) threats. For example, landscape conservation design, through assessment, acquisition and management, enhances connectivity while also providing natural corridors for species' migration, persistence and resilience (Bartuszevige et al. 2016). When used in conjunction with information on climate change and climate refugia (Morelli et al. 2016), as well as with projections of development and population growth, these frameworks can facilitate the identification and prioritization of habitat for conservation and connectivity that best support species under current and future conditions of risk. For instance, establishing a network of protected mangrove areas representing a range of different community types and maturity stages can support mangrove persistence in the face of SLR and other threats (Gilman et al. 2008).

Increasing coastal connectivity can also enhance storm protection services (Table 2). According to Barbier et al. (2008a), the relationship between wave attenuation and change in habitat area is nonlinear for salt marshes and mangroves, such that increasing habitat areas inland from the shoreline results in quadratic and exponential reductions in wave heights. Simulations using four hypothetical hurricanes at 12 locations along a shoreline transect (approximately 6 km in length) in the Caernarvon Basin in Louisiana, found storm surge levels were reduced by 1 m for every 9.4 to 12.6 km of additional wetlands along the transect (Barbier et al. 2013). Mangroves in Florida were also found to reduce peak surge levels by 0.4–0.5 m per km of mangrove forest width (Zhang et al. 2012). Beach, dune and barrier island restoration (e.g., dune building, beach nourishment), and limiting development to enable dynamic responses (e.g., breaches) to SLR and storms may be other important actions to increase protective services in some places (e.g., Defeo et al. 2009). The level of storm protection provided by beaches largely depends on the slope of the near-shore submerged environment, wave magnitude and sediment supply (NRC 2007; USACE 2013). Dunes also block waves and prevent inland inundation, depending on several similar factors (Barbier et al. 2008a; Temmerman et al. 2013). An exponential relationship was found between the percent cover of dune grasses and size of oceanic waves blocked by sand dunes, such that as the vegetation density and dune height increased, higher waves were needed to overtop the dune (Barbier et al. 2008b). Facilitating the establishment of dune grasses along the backshore of beaches and the use of sand fencing can help trap sands and create and maintain dunes (USEPA 2009); however, these beach stabilization approaches may conflict and thus need to be balanced with the need for sparsely vegetated areas on dynamic beaches for piping plover and other shorebird feeding and nesting areas (Lott et al. 2007).

Restoration of oyster habitat is a primary strategy to restore lost ecological functions and the broader socio-ecological benefits they provide, including storm protection services through wave attenuation (Table 2; Grabowski et al. 2012; Ferrario et al. 2014). However, oyster reef building and restoration is not effective everywhere. Oyster reef sills, which are often built along eroding shorelines, may not support viable oyster populations for protection against SLR if sited in the subtidal zone in high salinity areas (Baggett et al. 2015; Ridge et al. 2015; Walles et al. 2016). Further, the value of shoreline stabilization provided by oyster reef restoration can vary greatly by location, and restoration investments may not be recovered in places where oyster harvesting practices are particularly destructive (Grabowski et al. 2012).

Vegetated coastal habitats provide important carbon sequestration services and have more long-term potential than

Table 2 A selection of management approaches and their associated ecosystem services using tidal marshes, beaches and barrier islands, biogenic reefs, and mangroves as natural infrastructure to increase socio-ecological resilience to SLR and storms. Ecosystem services were categorized as: provisioning (♦), regulating (○), cultural (□), and supporting (●), as defined by MEA (2005). *Provisioning* refers to products obtained from ecosystems, like food and water; *regulating* describes benefits obtained from ecosystem regulation, such as climate-controlled processes; *cultural* describes non-material benefits from ecosystems, such as social heritage and a sense of place; and *supporting* describes the services needed to produce all other ecosystem services, e.g., nutrient and chemical cycling. All ecological benefits are considered supporting (for habitat) services

Management Approaches to Enhance Resilience to Sea Level Rise and Storms	Ecological Benefits	Human Community Benefits
Tidal Marsh Restoration: Tidal flows	● Restores natural functioning (such as by removing or mitigating a tidal restriction) ● Reduces marsh subsidence and collapse to keep pace with relative SLR ● Improves drainage to minimize flood impacts ● Supports native vegetation and increases water filtration ● Lowers threat and spread of invasive plants ● Improves habitat quality for a diversity of marsh-dependent species ● Moderates and restores natural salinity levels	○ Increases flood storage capacity ○ Preserves natural storm defenses ○ Improves water quality ○ Enhances climate change mitigation through carbon sequestration and storage, known as blue carbon □ Supports eco-tourism through fishing, hunting and wildlife viewing activities ● Provides habitat for recreational and commercial species
Tidal Marsh Restoration: Sediment augmentation	● Increases marsh persistence by supplementing accretion and elevation gain ● Helps reduce marsh subsidence and collapse by reversing wetland/marsh loss and prevents or delays conversion to open water ● Provides high and low marsh habitat for marsh-dependent species	○ Prolongs viability of marshes and associated flood risk and nutrient reduction benefits ○ Enhances climate change mitigation through carbon sequestration and storage, known as blue carbon ● Provides habitat for recreational and commercial species
Beach/Barrier Island Restoration: Remove barriers to dynamic sediment movement and allow breaches to occur in beach, dune, and barrier island systems	● Preserves, restores, and/or creates foraging, spawning, resting, and stopover habitat for many species, including those that are endangered, threatened, and declining ● Improves dune habitat and persistence against ongoing erosion and flood risks	○ Preserves natural storm defenses, particularly as a multiple lines of defense approach □ Enhances recreational opportunities □ Supports eco-tourism through fishing, hunting and wildlife viewing activities
Oyster Reef Restoration	● Stabilizes shorelines by enhancing sediment deposition behind reefs ● Serves as natural breakwater to help adjacent marshes and shorelines withstand storm surge and erosion ● Provides nursery habitat for fish and invertebrates ● Improves nearshore water quality, which supports seagrass growth ● Improves ecosystem connectivity between restored and nearby natural reefs and as a refuge structure for mobile organisms ● Supports coastal biodiversity, especially of species that attach to shells or utilize the spaces between them	♦ Increases resilience of the local economy by providing habitat for commercially and recreationally important fish and shellfish ♦ Increases oyster harvests ○ Preserves natural storm defenses ○ Slows shoreline retreat and erosion ○ Improves nearshore water quality □ Increases real estate value for protected properties ● Provides water filtration and nutrient removal, reducing risk of algal blooms and hypoxia
Coral Reef Restoration	● Provides sediment retention ● Supports biodiversity and productivity ● Provides nursery habitat for many marine species ● Reduces wave energy and associated impacts on adjacent habitats	○ Preserves natural storm defenses ○ Enhances climate change mitigation through carbon sequestration and storage, known as blue carbon □ Supports eco-tourism through fishing, hunting and wildlife viewing activities □ Enhances recreational opportunities ● Provides habitat for recreational and commercial species
Mangrove Restoration	● Supports biodiversity, especially of species that attach to roots or utilize the spaces between them ● Increases sediment capture and stabilization ● Promotes accretion and vertical land building to keep pace with SLR	♦ Increases resilience of the local economy by providing habitat for commercially and recreationally important fish and shellfish ○ Preserves natural storm defenses ○ Enhances climate change mitigation through carbon sequestration and storage, known as blue carbon

Table 2 (continued)

Management Approaches to Enhance Resilience to Sea Level Rise and Storms	Ecological Benefits	Human Community Benefits
		○ Improves water quality □ Enhances recreational opportunities
Landscape Conservation Design: Habitat migration through site assessment, acquisition, and management	● Allows focal coastal habitats to respond dynamically to SLR and storm impacts by moving into adjacent suitable areas ● Secures additional long-term protection of habitat for fish, plants, and wildlife ● Reduces habitat loss and degradation, such as through coastal squeezing ● Facilitates and maintains the diversity and juxtaposition of habitats required by many species	○ Preserves natural storm defenses ○ Prevents development in vulnerable coastal areas ○ Provides coastal landowners an option to sell their land that would be risky to develop for residential or commercial purposes
Landscape Conservation Design: Expanded network of conservation areas	● Supports an ecologically-connected network for species and population persistence and resilience ● Facilitates shifts in species' range, distribution, phenology and adaptation in response to changing conditions by providing corridors for migration and dispersal ● Facilitates and maintains the diversity and juxtaposition of habitats required by many species ● Secures freshwater and sediment inflows and increases tidal flows to support oysters, seagrasses, and other habitat-forming species	○ Increases flood storage capacity □ Enhances recreational opportunities □ Supports eco-tourism through fishing, hunting and wildlife viewing activities □ Increases real estate value for nearby properties
Living Shorelines: Planting native or climate tolerant vegetation and non-biogenic materials (e.g., coir logs, rock sills)	● Stabilizes shorelines and reduces erosion ● Protects and/or creates habitat for submerged aquatic vegetation, invertebrates, and other estuarine species ● Provides food resources and roost sites for waterbirds ● Provides habitat continuum for fish and wildlife migration between aquatic and terrestrial habitats ● Supports habitat migration within the shore zone and inland ● Reduces or reverses salt marsh habitat loss and degradation ● Improves water quality ● Provides attenuation benefits for boat wakes and storm driven waves	♦ Increases resilience of the local economy by providing habitat for commercially and recreationally important fish and shellfish ○ Preserves natural storm defenses ○ Enhances climate change mitigation through carbon sequestration and storage, known as blue carbon, if vegetation based (as opposed to cement or other structural material) ○ Reduces repair/maintenance costs after storms as natural systems have the capacity to self--repair □ Improves water quality □ Supports eco-tourism through fishing, hunting and wildlife viewing activities □ Enhances recreational opportunities □ Increases real estate value for protected properties
Facilitated Re-Location: Retreat from coasts (e.g., shoreline setbacks, rolling easements)	● Helps protect coastal ecosystems by reducing anthropogenic impacts such as from structures that inhibit dynamic responses of habitats (e.g., shoreline armoring) and from runoff that can increase water pollution ● Enables the natural migration of the shoreline up to a point by reducing impediments from the built environment, if based on long-term estimates of erosion or SLR ● Preserves habitat for vulnerable species, such as by prohibiting new development or construction within a certain distance from the coast	○ Steers development away from high-risk areas ○ Reduces flood risks and impacts to structures for a longer period of time (in areas with fixed setbacks or rolling easements) □ Lowers flood insurance costs in some situations through FEMA's Community Rating System □ Provides aesthetic improvements and increased views due to relocated structures □ Improves emergency management by reducing evacuations □ Provides private landowners with some flexibility in the use of their land if implemented through rolling easements, except construction of shoreline stabilization structures, though the landowner will incur costs due to erosion and flooding from encroaching shoreline

Table 2 (continued)

Management Approaches to Enhance Resilience to Sea Level Rise and Storms	Ecological Benefits	Human Community Benefits
		□ Preserves public access along eroding beaches for a longer period of time than would otherwise occur
Open Space Preservation: Preserve and restore natural open spaces through buyouts, acquisitions, and management	● Allows for the migration of marshes, mangroves and beaches in response to SLR ● Provides additional habitat protection for vulnerable species	♦ Results in higher real estate values for adjacent properties ○ Reduces flood risks and impacts to structures by preventing development in hazard-prone areas ○ Increases water storage capacity for flood risk reduction in neighboring areas □ Lowers flood insurance costs in some situations through FEMA's Community Rating System □ Provides aesthetic improvements and increased views due to fewer structures
Land Use Planning: Incorporate future conditions to extend current land use planning horizons	● Informs actions that address the long-term impacts of SLR and coastal storms on species and habitats ● Supports the long-term integrity and functioning of coastal habitats	○ Steers development away from high-risk areas □ Minimizes maintenance, augmentation costs over a structure's design life □ Facilitates planning habitat restoration and management projects, especially for selecting appropriate sites for action ○ Lowers flood insurance costs in some situations through FEMA's Community Rating System

Many of the natural infrastructure solutions and adaptation strategies listed in Table 2 are included in the Coastal Ecosystems Background Paper for the National Fish, Wildlife and Plants Climate Adaptation Strategy, online at: https://www.wildlifeadaptationstrategy.gov/pdf/Coastal_Ecosystems_Paper.pdf

terrestrial forests due to higher rates of organic carbon burial in sediments (McLeod et al. 2011). Restored tidal marsh and mangroves may offer more carbon benefits relative to newly created wetlands or through passive management approaches (Kroeger et al. 2017). The global value of coastal vegetated sequestration is between \$6.1 and \$42 billion USD annually, while conversion and degradation of these habitats can release between 0.15 and 1.02 billion tons of carbon dioxide per year (Pendleton et al. 2012). In Massachusetts, a 20-acre restoration project that removed two culverts to restore tidal flows to a salt marsh showed a net increase in carbon sequestration of 76 metric tons of carbon dioxide per year. Another 60-acre restoration project removed over four feet of wetland fill to restore salt marsh and grassland habitat, which led to a net increase in carbon sequestration of 101 metric tons of carbon dioxide per year (MA DER 2012; 2014). The differences in carbon sequestration rates between these restoration sites may be due to the amount of carbon sequestered by various habitat types, such as high versus low saltmarsh and filled uplands versus coastal grasslands (MA DER 2014).

Lastly, adaptive frameworks and decision support tools that allow managers to integrate and continuously update predictions of risk from climate change, land use and human population growth projections can increase the effectiveness of the types of natural infrastructure described in Table 2 and support short- and long-term biological, cultural, social, and economic goals (e.g., Bartuszevige et al. 2016; Anderson and Barnett 2017). The consideration of quantitative thresholds to climate and other stressors can also help establish management targets and timelines (Powell et al. 2017). For example, when sediment augmentation is used as an approach for tidal marsh restoration, SLR and storm projections along with threshold data for marsh habitats can guide the frequency and amount of sediment deposition, monitoring and maintenance needed to keep pace with gradual and episodic changes (Foley et al. 2015). Other management options (e.g., retreat from coasts and open space preservation) focus on risk reduction by moving people and property out of harm's way, often with economic incentives like flood insurance discounts. When combined with other zoning and land use protections, these actions can create secondary and tertiary benefits of increasing the persistence and resilience of natural habitats and species. For example, managing lands after the re-location of people or infrastructure in the coastal zone can enable the natural migration of coastal systems as needed in response to relative SLR. More information about how to apply these and other adaptation approaches is available through the Massachusetts Wildlife Climate Action Tool (https://climateactiontool.org).

A comparison of management approaches utilizing natural infrastructure and traditional grey infrastructure

Grey infrastructure has long been used to protect coastal communities from wave impacts, flooding and erosion. However, the myriad benefits that natural infrastructure can provide to ecological and human communities (Table 2) has made them an increasingly attractive alternative to grey infrastructure. In addition, research shows that restoration and management using natural infrastructure can be equally or more successful than grey infrastructure for flood risk reduction when implemented in appropriate places (e.g., Gedan et al. 2010; Temmerman et al. 2013; Jonkman et al. 2013; Small-Lorenz et al. 2016; Bayraktarov et al. 2016).

Natural infrastructure is naturally dynamic and in many ways resilient to the threats from SLR and storms, because it has some capacity to self-repair with minimal maintenance (Temmerman and Kirwan 2015). Conversely, grey infrastructure requires costly repairs following catastrophic storms, augmentation such as increased seawall heights to keep pace with rising actuarial risks, regular maintenance to delay deterioration and prolong design life, as well as eventual replacement (Temmerman et al. 2013; National Science and Technology Council 2015). In addition, grey infrastructure can adversely impact the surrounding natural environment in many ways, such as through loss of sediment (NRC 2007), decreases in beach volume and dimension (Kraus and Pilkey 1988; Hill 2015), and loss of intertidal habitat (NRC 2007; USEPA 2009; National Science and Technology Council 2015). Grey infrastructure can further lead to habitat fragmentation, declines in biodiversity, increases in invasive species, and reduced habitat migration inland in response to SLR (Bilkovic et al. 2016 and references within). These adverse impacts can degrade or inhibit ecosystem services provided by coastal habitats located adjacent to grey infrastructure.

Hybrid approaches that combine natural and grey infrastructure have been shown to contribute to societal, economic and environmental goals (e.g., National Science and Technology Council 2015). However, more information about the relative benefits and costs is needed to inform decisions on the use of each approach (grey, natural) alone or in concert (Sutton-Grier et al. 2015). As a starting point to address this need, we synthesized examples of coastal management and restoration actions with their corresponding economic and/or ecological derived value estimates (Table 3). We note that while these estimates provide some indication of the relative economic benefits, high uncertainty remains and may have limited transferability from one location to another, particularly if valuations are based on a single site.

Natural infrastructure

There is an increasing number of studies demonstrating the cost-effectiveness of using natural infrastructure for coastal risk reduction (e.g., Gedan et al. 2010; Grabowski et al. 2012; Temmerman et al. 2013; Barbier 2013; Abt Associates 2014; Temmerman and Kirwan 2015; Martin and Watson 2016; Small-Lorenz et al. 2016; Narayan et al. 2016; Reguero et al. 2018). A synthesis study of restoration projects worldwide found costs and success rates vary by habitat, with mangroves requiring relatively lower investment in comparison to seagrasses, salt marshes and oyster reefs (Bayraktarov et al. 2016). Restoration of salt marshes and coral reefs exhibited the greatest success with annual survival rates of 64.8% and 64.5%, respectively, while seagrass habitats had the lowest post-restoration annual survival rates with a median survival rate of 38% (Bayraktarov et al. 2016). Grabowski et al. (2012) analyzed the cost-benefit ratio of oyster reefs and found that restoration costs are typically recovered in 2–14 years, depending on where restoration occurs and the range of services achieved. Overall, the costs associated with natural infrastructure vary widely and depend on many factors, such as design specifications, size and location of project, materials, maintenance, and disturbances that determine how often and the degree to which maintenance and rebuilding are required (NRC 2014). Restored or created habitats and their ecosystem services generally require several years to decades to become well established (NRC 2007; Temmerman et al. 2013), while hard structures can often be built quickly and offer immediate flood protection to surrounding communities.

There remains high uncertainty in the relative effectiveness of natural infrastructure for services like flood risk reduction compared to traditional grey infrastructure. Existing information on flood risk reduction and erosion control has been largely anecdotal to date; this lack of concrete evidence likely inhibits implementation of natural infrastructure, even in cases where it may be less costly than grey infrastructure over the long term. Consequently, it is important to increase the number of valuation studies that definitively link natural infrastructure to the full suite of potential ecosystem and economic benefits, including those that are not traditionally marketed such as flood protection (Table 3) (Barbier 2013).

The global value of ecosystem services provided by natural infrastructure could decline by as much as $51 trillion USD per year or increase by $30 trillion per year based on four alternative global land use and management scenarios (Kubiszewski et al. 2017). Therefore, better communication and public outreach about the costs and benefits of natural infrastructure is critical to ensure decision makers and planners have all existing options available to them to inform action.

Grey infrastructure

Grey infrastructure, such as seawalls, storm surge barriers, dikes, and levees, have been used for decades for protection from storms and flooding. However, these approaches can have unintended negative impacts to habitats that can ultimately undermine the additional flood protection and other services that coastal habitats provide. Hard structures that parallel shores reflect wave energy and constrain the natural

Table 3 Selected coastal management actions using grey, natural and hybrid infrastructure and corresponding estimates of their value as ecosystem services for coastal storm protection

Coastal management approach		Ecosystem benefit / value estimates (USD, %, or surge protection in m)	Geographic location or extent of derived benefits
1. Natural Infrastructure	a. Tidal Marsh Restoration	1. $23.2 billion annually in storm protection services based on an average swath of wetland area of 100 km × 100 km (Costanza et al. 2008) 2. $625 million in avoided flood damages (Narayan et al. 2017) 3. 16% reduction in average annual flood losses (Narayan et al. 2017) 4. A 1% increase in wetland continuity results in an 8–11% reduction in storm surge; a 0.1 increase in the wetland-water ratio per meter will reduce residential flood damages by $99 to $133 (Barbier 2013)	1. Model-based estimates from 34 US landfalling hurricanes since 1980 2. 12 coastal states from Maine to North Carolina, USA 3. Ocean County, New Jersey, USA 4. 12 locations along a transect in the Caernarvon Basin in southeastern Louisiana, USA
	a. Beach / Barrier Island Restoration	1. Total value of $141 million annually in storm protection services (2013 dollars, replacement cost equivalent) (Taylor et al. 2015) 2. As dune plant density increases over time from 25% to 85%, increasingly higher waves of 6.5 m to 13 m, respectively, are required to overtop the dune (Barbier et al. 2008b)	1. Mustang and North Padre Islands, Texas, USA 2. Oregon coast, USA
	b. Mangrove Restoration	1. Peak surge levels reduced by 0.4–0.5 m per kilometer of forest width in Florida (Zhang et al. 2012) 2. Provides between $200,000 and $900,000 per hectare annually in total products and services (Wells et al. 2006)	1. Gulf Coast of South Florida, USA, from Sanibel Island to Key West 2. Global estimate
	c. Oyster Reef Restoration	1. Economic value of services from restored and protected oyster reefs, excluding oyster harvesting, is between $5,500 and $99,000 per hectare per year (Grabowski et al. 2012) 2. Two oyster reef projects with a total length of 5.8 km will produce 51%–90% reduction in wave height and 76%–99% reduction in wave energy at the shore (Kroeger 2012)	1. Average of US estimates based on a literature synthesis 2. Two restoration sites in Mobile Bay, Alabama, USA
	d. Coral Reef Restoration	1. Provides between $100,000 and $600,000 per square km annually in total products and services (Wells et al. 2006) 2. Coral reefs reduce wave energy by an average of 97% across approximately 800 m of a shoreline transect consisting of a reef crest and reef flat, which translates to a 64% reduction in wave height (Ferrario et al. 2014)	1. Global estimate 2. Meta-analysis covering reefs across the Atlantic, Pacific and Indian Oceans
2. Grey Infrastructure	a. Storm Surge Barriers, Levees, and Seawalls	1. $234 million (2013 dollars) in avoided flood damages from Hurricane Alicia in 1983 (NRC 2014) 2. Hurricane barriers can prevent roughly $96 million (2013 dollars) in flood and storm damages (NRC 2014) 3. Typical design standards are for protection against a 100-year storm, corresponding to an average surge level of 3–6 m and wave height of 1–2.5 m (Jonkman et al. 2013)	1. Galveston, Texas, USA 2. Stamford, Connecticut, USA 3. New Orleans, Louisiana, USA
3. Hybrid Approaches	b. Living Shorelines	1. 90% reduction in wave heights within 20 m of the marsh edge from *Spartina alterniflora* dominated salt marshes (Knutson et al. 1982) 2. One-year-old living shorelines reduced wave energy by up to 67% from boat wakes (Manis et al. 2015)	1. Model-based simulations and field tests in North Carolina, USA 2. Mosquito Lagoon estuary, Florida, USA

inland migration of the shoreline in response to erosion, ultimately causing beaches to become narrower and the beach seaward of the structure to drown (Defeo et al. 2009). This coastal squeezing (Doody 2004; Torio and Chmura 2013) can disrupt normal sediment dynamics, lower the diversity and abundance of biota, and lead to habitat loss (Galbraith et al. 2002; Defeo et al. 2009). Revetments, which are sloping structures made of riprap, concrete mats, timber, or other materials to stop shoreline erosion, can be effective for erosion control if designed and constructed properly. But if revetments are improperly sited on eroding shores, they can accelerate loss of intertidal habitat behind and adjacent to them, causing the beach to convert to open water (NRC 2007). Groins and breakwaters, which are shore-perpendicular and shore-parallel structures, respectively, can similarly reduce sediment supplies in downdrift beaches, causing or accelerating erosion on the inshore sides of the barrier and narrowing or reducing beach habitat (NRC 2007; USEPA 2009).

Grey infrastructure combined with other coastal development and land use changes can lead to further losses in the ecosystem services that coastal habitats provide to society (Table 2; Bayraktarov et al. 2016). For example, dams restrict natural sediment loads needed for salt marsh accretion and maintenance (Weston 2014), decrease geomorphic stability, and degrade salt marsh habitats (Deegan et al. 2012). Grey infrastructure near mangrove habitat can convert mangrove forests to deep water by causing scouring along the front of structures and to downdrift areas (Gilman et al. 2008). Bulkheads can degrade spawning and nursery habitat, while also increasing shoreline erosion. When bulkheads are used to replace degraded vegetated habitats, the water quality improvement function of native vegetation is lost (NRC 2007; Currin et al. 2010).

The direct costs associated with grey infrastructure are well understood due to their long-term implementation, and from being designed according to well-vetted specifications. However, grey infrastructure can generate hidden costs over their design life due to degradation and gradual failure (RAE 2015). In addition, damages caused by these structures to surrounding ecosystems have not yet been fully quantified and documented (RAE 2015). While habitat restoration can be expensive (e.g., Bayraktarov et al. 2016), when represented as average costs per linear foot, the estimated costs of grey infrastructure are generally greater compared to non-structural and hybrid approaches (CCRM 2014).

Hybrid approaches

Hybrid approaches combine grey and natural infrastructure to varying degrees to maximize flood defenses and additional benefits (e.g., Sutton-Grier et al. 2015; Bridges et al. 2015). In some scenarios and locations, hybrid approaches provide the greatest flood protection benefit to coastal communities (USACE 2013; NOAA 2015; Schuster and Doerr 2015). Breakwaters and sills are common in marshes, mangroves and sandy dunes to help attenuate waves and stabilize sediments (NRC 2007). Sills are typically built of oyster shell or granite and placed on the seaward-side of a marsh or mangrove (Sutton-Grier et al. 2015), while breakwaters are generally made of timber, rock or concrete and placed further offshore than sills (RAE 2015). Mangroves can particularly benefit from hybrid shoreline stabilization approaches that use sills and breakwaters to reduce wave energy and maintain calm, low energy conditions that mangroves need to thrive (NRC 2007 and references within). Living shoreline techniques are often hybrid approaches that pair biogenic species and plantings with hardened infrastructure for shoreline protection. For instance, the creation of fringing marsh through plantings may be augmented by the installation of rock sills or other artificial breakwaters along the seaward edge and parallel to the marsh.

More novel hybrid approaches include the use of natural infrastructure to protect permanent and temporary grey infrastructure from storms and waves until the natural features mature and become well established (Sutton-Grier et al. 2015). For instance, oyster reefs located seaward of armored shorelines serve as natural breakwaters that attenuate wave energy and, thus, lessen the impacts of storms, while promoting sediment deposition shoreward of the reef and mitigating habitat loss caused by the existing grey infrastructure (USEPA 2009; Scyphers et al. 2011; Baggett et al. 2015).

When living shorelines are used alone or as hybrid approaches, monitoring results suggest these installments can be effective for enhancing coastal resilience. In Maryland, over 300 marsh fringe sites have been constructed and monitored over a 20-year period, demonstrating they have been effective for erosion control and wetland habitat creation (NRC 2007 and references within). Like many of the approaches discussed in this study, the costs of living shoreline projects can vary greatly with location (RAE 2015) and are not appropriate or effective everywhere. Initial costs can be significantly less than those for grey infrastructure, yet long-term costs will depend on whether and how frequently the living shoreline must be repaired or rebuilt (Titus et al. 2009; Temmerman et al. 2013; Bilkovic et al. 2016).

The future of natural infrastructure: opportunities and limitations

The implementation of natural infrastructure alone or through hybrid approaches to enhance resilience to SLR, storms and other coastal stressors is becoming more widespread in practice (DOI Metrics Expert Group 2015; Abt Associates 2015, 2016; MARCO and NWF 2017). Currently, however, managers have limited opportunities to directly compare risk reduction benefits and costs with traditional grey infrastructure. Regulatory barriers, coupled with lack of public awareness and contractor knowledge of the long-term services provided by natural infrastructure, have impeded permitting processes, which remain cumbersome compared to grey infrastructure. Streamlined guidance for the implementation of natural infrastructure, especially following storms and other extreme events, could give communities greater confidence and advance their application. In particular, best practices for site selection and the conditions where natural infrastructure can be most effective for maximizing socio-ecological benefits are still needed (Bayraktarov et al. 2016; Jahn 2016).

Ecosystem service valuation represents a growing opportunity for enhanced socio-ecological resilience planning and more informed decision-making. Additional studies with greater geographical coverage, consistent terminology, and methodologies for quantifying and valuing services, particularly non-marketed and indirect ecosystem services, would help increase awareness of the total benefits related to natural infrastructure (Barbier 2013; Olander et al. 2015). Lastly, uncertainty about how climate change will impact ecosystem services, including linking changes in ecosystem structure and function to the production of goods and services, limits management and decision making in this arena (Barbier 2013).

Preliminary, yet rapidly, maturing information on natural infrastructure and hybrid approaches can be used to take action and integrate their benefits into resilience planning guidelines. Here, we present potential actions that can increase information and reduce uncertainty around the use of natural infrastructure in coastal planning processes.

1) Substantially increase performance evaluation and widespread monitoring of natural infrastructure.

- Identify and develop best practices, clear monitoring goals and standardized post-implementation performance evaluations.
- Communicate and disseminate results more widely, particularly when surprises and complications occur (Jahn 2016; MARCO and NWF 2017).
- Explore innovative approaches and funding mechanisms for increasing data and long-term monitoring of restoration before and after project implementation, such as using citizen science networks (MARCO and NWF 2017).
- Where possible, use quantitative thresholds to stressors to inform decisions regarding site selection, design, and implementation of natural infrastructure and hybrid approaches (Adger et al. 2009; Stein et al. 2013; Stein et al. 2014; Powell et al. 2017).
- Develop scenarios to increase understanding of how resilient natural infrastructure may be at different locations, under future conditions, and timelines to thresholds that may affect habitats and ecosystem services.

2) Increase information on the potential benefits and costs of natural, grey and hybrid approaches for decision-making in the coastal zone.

- Develop and expand standardized long-term monitoring protocols and common metrics to clarify how natural infrastructure performs relative to traditional armoring practices.
- Expand cost-benefit analyses to account for the cumulative services accrued by natural infrastructure in comparison to grey infrastructure, as well as long-term maintenance and augmentation costs of both approaches.
- Increase research to clarify the link between natural infrastructure and potential ecosystem services, as well as the extent to which grey infrastructure affects ecosystem services.
- Increase synthesis of studies on ecosystem service valuation related to natural infrastructure to stimulate new research and reduce data gaps.
- Increase assessment of the potential benefits of natural infrastructure for carbon sequestration (Bianchi et al. 2013; Jerath et al. 2016; Yando et al. 2016).

3) Increase coordination and planning around socio-ecological resilience goals.

- Better communicate the potential benefits of coastal habitats and biodiversity as part of a broader community adaptation strategy (Mawdsley et al. 2009; NASEM 2016).
- Increase outreach to landowners as part of planning processes to facilitate prioritization of areas where land acquisition may be the best option for autonomous change.
- Seek opportunities to communicate and integrate the full range of ecosystem services derived from natural infrastructure into community resilience planning and decision making (e.g., Grimm et al. 2013; Nelson et al. 2013; Grimm et al. 2016).
- Engage state agencies as part of project planning and implementation processes (USEPA 2009). For instance, a best practice for development of State Wildlife Action Plans (SWAPs) is to invite representatives of municipal, county and/or regional planning entities to serve on conservation plan committees (Association of Fish and Wildlife Agencies 2012).
- Take advantage of regular planning cycles (e.g., SWAPs, hazard mitigation, comprehensive/land use) to coordinate socio-ecological resilience goals. While timeframes differ, these activities bring multiple partners and stakeholders together to identify shared priorities, develop strategies, and inform each other's benchmarks, successes and challenges.

Conclusions

Coastal management strategies that incorporate natural infrastructure and hybrid approaches provide opportunities for risk reduction and coordination around shared socioeconomic and ecological goals. Studies on climate resilience have grown rapidly in recent years (Fisichelli et al. 2016) and are increasingly being considered in practices related to coastal protection, restoration and management (Mawdsley et al. 2009; NOAA 2010; Stein et al. 2014; Schuster and Doerr 2015; Staudinger et al. 2015; NOAA 2016; USFWS 2016), as well as national assessments and agency operations (e.g., USACE 2014; iCASS 2016). Recent federal efforts, such as the Gulf Coast Ecosystem Restoration Council (2013) and the U.S. Department of the Interior's Hurricane Sandy Coastal Resiliency Competitive Grant Program that were established in response to major disasters, have helped to advance implementation of coastal adaptation strategies for enhanced socio-ecological resilience at federal, state and local levels. Nonetheless, challenges to systematic implementation of natural infrastructure for enhanced coastal resilience remain, and many practitioners have limited resources to keep up with this rapidly advancing field.

To meet this need, this study provides a comprehensive overview of the current knowledge of how tidal marshes, beaches and barrier islands, biogenic reefs, and mangroves have been used as natural infrastructure to enhance coastal resilience in response to SLR and coastal storms along the United States Atlantic, Gulf, and Caribbean coasts. Our summary demonstrates that investments in natural infrastructure in the coastal zone can have measured value for coastal communities while increasing ecological persistence and resilience. However, information is highly nuanced and spatially variable. More research is needed to develop best practices for where a particular natural infrastructure may be most effectively applied and what can realistically be expected in terms of performance and derived ecosystem services. Natural infrastructure may not be the best option in some locations, and grey infrastructure or hybrid approaches may perform better depending on the local landscape and socio-ecological goals. Regardless, ensuring coastal managers and planners are aware of all potential options and of the short- and long-term costs and benefits is key for advancing this field.

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