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Review

Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems



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ARTICLE INFO

Article history:

Available online 28 April 2015

Keywords:

Ecosystem services

Storm protection

Coastal flooding

Storm surge

Community resilience

ABSTRACT

There is substantial evidence that natural infrastructure (i.e., healthy ecosystems) and combinations of natural and built infrastructure (“hybrid” approaches) enhance coastal resilience by providing important storm and coastal flooding protection, while also providing other benefits. There is growing interest in the U.S., as well as around the world, to use natural infrastructure to help coastal communities become more resilient to extreme events and reduce the risk of coastal flooding. Here we highlight strengths and weaknesses of the coastal protection benefits provided by built infrastructure, natural ecosystems, and the innovative opportunities to combine the two into hybrid approaches for coastal protection. We also examine some case studies where hybrid approaches are being implemented to improve coastal resilience as well as some of the policy challenges that can make implementation of these approaches more difficult. The case studies we examine are largely in the U.S. but also include a couple of international examples as well. Based on this analysis, we conclude that coastal communities and other decision makers need better information in order to incorporate ecosystem protection and restoration into coastal resilience planning efforts. As additional projects are developed, it is important to capitalize on every opportunity to learn more about the cost of natural and hybrid infrastructure projects, the value of the storm and erosion protection benefits provided, and the full suite of co-benefits provided by healthy coastal ecosystems. We highlight top priorities for research, investment in, and application of natural and hybrid approaches. These data are critical to facilitate adoption of these approaches in planning and decision-making at all levels to enhance the resilience of our coasts.

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<http://dx.doi.org/10.1016/j.envsci.2015.04.006>

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1. Introduction

Coastal flooding due to extreme weather events and sea level rise is of growing global concern (IPCC Working Group II, 2014), and increasing coastal resilience to these threats is a priority for many countries and a global need (Barbier, 2014). The United States is no exception. In the U.S., in 2012, there were 11 weather and climate disaster events across the United States, including Hurricane Sandy. Nationally, these disaster events cumulatively caused 377 deaths and over \$110 billion in damages. This makes 2012 the second costliest year on record in the U.S., ranking only behind 2005, which incurred \$160 billion in damages due in part to four devastating coastal hurricanes (National Climatic Data Center (NCDC), 2013). In the wake of these major hurricanes and in the face of increasing chronic risks such as coastal flooding due to sea level rise (Shepard et al., 2012), the resilience of U.S. coastlines has emerged as a major socioeconomic and environmental concern for the federal government. For example, community resilience is specifically called out in the President's Executive Order 13653, "Preparing the United States for the Impacts of Climate Change" (The White House, 2013). In this Executive Order resilience is defined as "the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions," and building community resilience is a specific goal of the Executive Order actions. At the U.S. National Oceanic and Atmospheric Administration (NOAA), resilience fundamentally is thought to have at its core three components, or pillars – society, economy, and environment – that must all be healthy and robust for a community to be resilient (NOAA, 2010). Thus, the important role that coastal ecosystems can play in increasing coastal resilience is of growing interest.

Here, based on a synthesis review of existing peer-reviewed literature as well as several published reports, we highlight strengths and weaknesses of the coastal protection benefits provided by built infrastructure, natural ecosystems, and we examine in more depth the innovative opportunities to combine the two into "hybrid" approaches for coastal protection. Specifically, we examine some case studies where

hybrid approaches are being implemented to improve coastal resilience and we explore some of the policy challenges that can make implementation of these approaches more difficult. Notably, this article has a strong U.S. focus because the authors are most familiar with the policy needs and opportunities in the U.S., however, we feature case studies from both the U.S. and from other countries around the world where these approaches are gaining momentum. Much of what we conclude regarding opportunities for increasing coastal resilience using natural or hybrid approaches is relevant for coastal countries around the world.

2. United States policy framework for coastal resilience

In the U.S., as in many countries around the world, the coasts are not only a place where many people want to live (home to nearly four in ten Americans), they are also important economic engines and centers for commerce for the entire country (NOAA, 2014). In 2011, coastal shoreline counties contributed \$6.6 trillion to the U.S. Gross Domestic Product (GDP) – just under half of GDP that year (NOAA, 2012). In the face of climate change, it is critical to the health and prosperity of communities and the economy to think differently about managing and conserving U.S. shorelines. In particular, infrastructure, both healthy coastal ecosystems ("natural") and built ("gray") (Fig. 1) helps protect U.S. coasts from extreme events. To date, built infrastructure, including sea walls, levees, culverts, bulkheads, and other hardened structures, have dominated thinking about coastal protection (Spalding et al., 2014). However, there is an increasing body of evidence (see Section 3) that natural habitats, including wetlands, dunes, barrier islands, sea grasses, coral and oyster reefs, and mangroves reduce the risk of coastal flooding and erosion and provide other social and economic benefits – benefits that meet and cut across the three pillars of resilience. In addition there are also exciting opportunities for designing shorelines that include a combination of natural and built infrastructure (termed "hybrid" infrastructure, Fig. 2, and Section 3). These natural and hybrid approaches may be more



Fig. 1 – Examples of natural (top row) and built (bottom row) infrastructure. Photo Credits: NOAA for all images except Dunes (credit: American Green), Sea Wall (credit: University of Hawaii Sea Grant), and Levee (credit: J. Lehto, NOAA).

Minimal Defense

Many communities have developed right along the ocean with only minimal natural defenses from a small strip of beach between them and the ocean.

Natural

Natural habitats that can provide storm protection include salt marsh, oyster and coral reefs, mangroves, seagrasses, dunes, and barrier islands. A combination of natural habitats can be used to provide more protection, as seen in this figure. Communities could restore or create a barrier island, followed by oyster reefs and salt marsh. Temporary infrastructure (such as a removable sea wall) can protect natural infrastructure as it gets established.

Managed Realignment

Natural infrastructure can be used to protect built infrastructure in order to help the built infrastructure have a longer lifetime and to provide more storm protection benefits. In managed realignment, communities are moving sea walls farther away from the ocean edge, closer to the community and allowing natural infrastructure to recruit between the ocean edge and the sea wall.

Hybrid

In the hybrid approach, specific built infrastructure, such as removable sea walls or openable flood gates (as shown here) are installed simultaneously with restored or created natural infrastructure, such as salt marsh and oyster reefs. Other options include moving houses away from the water and raising them on stilts. The natural infrastructure provides key storm protection benefits for small to medium storms and then when a large storm is expected, the built infrastructure is used for additional protection.

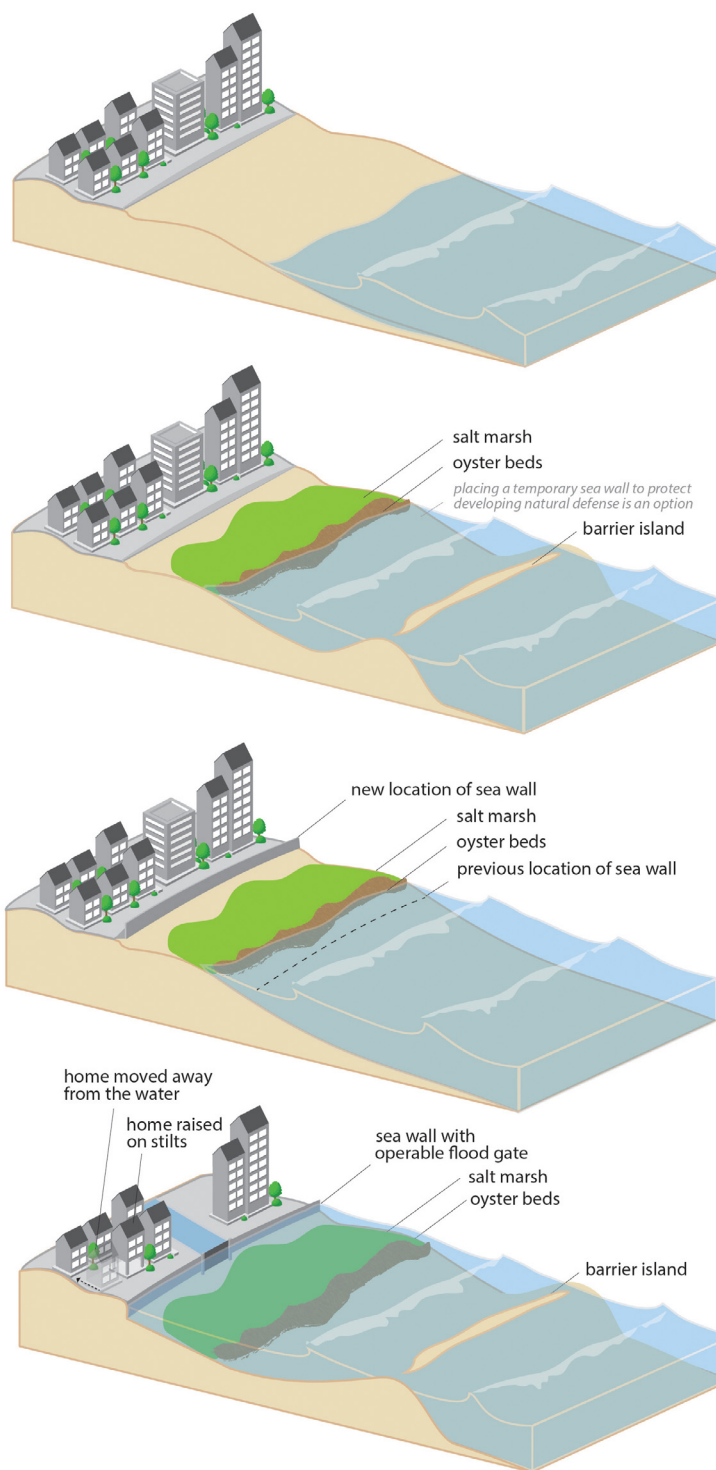


Fig. 2 – Examples of coastal defenses including natural infrastructure, managed realignment, and hybrid approaches.

cost-effective in the long-run in comparison to built infrastructure, can strengthen the social, economic and ecological resilience of coasts, maintain the provisioning of coastal ecosystem services, and prevent the loss of life and property.

The time is also ripe to enhance coastal resilience by incorporating natural and hybrid infrastructure into coastal policy and planning. In the U.S., there has never before been

such high-level attention within the federal sector on using natural and restored features along the coasts to reduce vulnerability to natural hazards and disasters. Hurricane Sandy was a catalyst for noticeably increased Federal interest in the use of natural infrastructure for coastal protection. For example, the President's Hurricane Sandy Rebuilding Task Force focused significant attention on building resilient

infrastructure as a key component of the \$50 billion Disaster Relief Appropriations Act, known as the Sandy Supplemental (113th Congress of the United States of America, 2013). This resulted in, for the first time, a set of Presidential Task Force guidelines calling for environmentally sustainable and innovative solutions that consider natural infrastructure options in all Federal Sandy infrastructure investments. The Task Force worked across Federal agencies and with the private sector to ensure that communities interested in pursuing natural infrastructure solutions to enhancing resilience have access to data and tools that can assist them in evaluating how natural infrastructure can be integrated into their recovery or future risk reduction strategies. The lead agencies made a range of tools available to State and local partners, including modeling capabilities, decision support tools, case studies, and best management practices. Interagency sharing also helped identify critical information and decision support needs necessary for investment decisions, while limiting duplicative efforts. A focused effort was thus orchestrated to implement natural infrastructure approaches in Sandy rebuilding, and further to provide transferable methods for advancing these approaches – including through consistent approaches to value their benefits – beyond the Sandy-affected region (Hurricane Sandy Rebuilding Task Force, 2014).

The President's Climate Action Plan also underscores the importance of resilient infrastructure approaches and calls for using natural ecosystems, including forests and wetlands, to help sequester carbon and mitigate the effects of climate change (Executive Office of the President, 2013). The recognition of the climate mitigation benefits of natural ecosystems is timely, given that one of the top vulnerabilities and risks to society due to climate change in the newly released Intergovernmental Panel on Climate Change (IPCC) Report is injury or death from sea-level rise, storm surge, and coastal flooding (IPCC Working Group II, 2014).

In part because of the increased attention from the U.S. federal government, there are expanded efforts to include coastal ecosystem protection and restoration as part of coastal adaptation strategies, and a growing interest among coastal planners at state and local levels to consider natural (or “green”) along with built infrastructure in protecting our coastlines and communities. Thus, as the U.S. re-envisioned how to increase the resilience of its coastal communities, there is significant potential for coastal ecosystems to play an important role in reducing storm and erosional impacts. Of note, in addition to providing protection from extreme events, coastal ecosystems strengthen resilience to chronic flooding. This is key, as most costs from natural hazards come from localized, smaller events (Axley, 2013). As sea level continues to rise, the ability of natural infrastructure to absorb chronic impacts may become even more important.

3. Status of our knowledge

3.1. The value of storm protection benefits

One of the key questions about natural infrastructure is the value of the benefits provided by these systems. In other words, do these systems provide a measurable amount of

storm protection benefits? Based on our synthesis, we determined that, where data are available, the resilience and protective benefits provided by coastal ecosystems against waves, floods and storm surge is very valuable. Coastal wetlands in the U.S., for example, were estimated to provide \$23.2 billion per year in storm protection services alone based on a regression model of 34 major hurricanes to hit the U.S. since 1980; a loss of 1 ha of wetland in the model corresponded with increased average storm damages of \$33,000 from specific storms (Costanza et al., 2008). Another estimate for southeast Louisiana determined that coastal wetlands demonstrably reduced storm surge and that a 0.1 increase in the ratio of wetland to open water resulted in saving three to five properties – avoiding damages estimated between \$590,000 and \$792,000 – for a given storm (Barbier et al., 2013). That said, there are relatively few studies that have quantified the value of natural ecosystems for storm and erosion protection and to our knowledge, no one has assessed the value of hybrid approaches to date in the peer-reviewed literature.

Further, it is important to recognize that the benefits of natural and hybrid approaches are not limited to the value of coastal protection they provide but include many co-benefits that are key to strengthening the three pillars of resilience. For example, the Nature Conservancy (TNC), in particular, has been working with the private sector and other partners to investigate the cost-benefit ratios of natural and hybrid tactics. In one project where TNC installed oyster reefs in the Gulf of Mexico, they found that, in addition to significant reductions in height and energy among the highest 10% of waves, 5.6 km of oyster reef translated to more than 6900 pounds of additional catch per year (39% commercial and 61% recreational) and removal of up to 1888 kilograms of nitrogen per year from surrounding nearshore waters. TNC has only begun to estimate what this means in terms of return on investment, thus far calculating that based on the net present value of fishery enhancements alone, benefits received would exceed restoration costs (\$4.28 M) in year 34 of the project. Importantly, though, this project could bring a return on investment sooner if it were easier to assess the benefits of coastal protection and nitrogen cycling (The Nature Conservancy et al., 2013b). Some of these co-benefits can be difficult to measure and value, but whether we can measure and value the benefits or not, natural infrastructure can consistently provide many valuable co-benefits to coastal communities that can help to secure community resilience. Built infrastructure, on the other hand, is limited in that it only provides coastal protection value and only during storm events.

Indeed, many of the co-benefits associated with natural infrastructure are precisely what make coastal areas so valuable and what draws people to live and work in these oft-vulnerable regions. The coastal ecosystems that enhance resilience by providing protective services also contribute raw goods and materials, plant and animal habitat, water and air quality regulation, carbon sequestration, nutrient cycling, and opportunities for tourism, recreation, education, and research (Barbier et al., 2011). Natural infrastructure projects implemented for the purpose of reducing vulnerability often can simultaneously achieve additional societal, environmental, and economic objectives. These early successes have helped

to gain more support across governments, the private sector, engineers, and financiers. Compared to years past, there is an enormous investment of federal dollars and energy being targeted toward the implementation of natural infrastructure approaches. This is allowing the reimagining of our coasts with increased momentum toward incorporating natural and hybrid approaches for building coastal resilience. However, this increased U.S. federal focus on natural and hybrid approaches also necessitates a review of the effectiveness of

different ecosystems in providing storm and erosional benefits in order to understand what level of protection can be expected from which coastal ecosystems and under what conditions.

3.2. Status of our knowledge on coastal protection benefits of built and natural infrastructure

Built infrastructure and natural infrastructure have different strengths and weaknesses (Table 1). Built infrastructure is well

Table 1 – Summary of infrastructure strengths and weaknesses by type.

Infrastructure type	Strengths	Weaknesses
Built (seawalls, levees, bulkheads, etc.)	<ul style="list-style-type: none"> • Significant expertise already exist on how to design and build such approaches • Decades of experience with implementing this approach • Excellent understanding of how these approaches function and what level of protection will be provided by different types of structures built to specific engineering standards • Ready to withstand a storm event as soon as they are constructed 	<ul style="list-style-type: none"> • Does not adapt with changing conditions such as sea-level rise • Weakens with time and has a built-in lifetime • Can cause coastal habitat loss and have negative impacts on the ecosystem services provided by nearby coastal ecosystems • Can lull communities into thinking they are safe from all disasters leading to increased loss of life or property • May sustain more damage during small storm events than natural approaches • Only provides storm protection benefits when a storm is approaching; no co-benefits accrue in good weather
Natural (salt marsh, mangrove, beach, dune, oyster and coral reefs, etc.)	<ul style="list-style-type: none"> • Provides many co-benefits in addition to coastal protection including fishery habitat, water quality improvements, carbon sequestration and storage, and recreational use, and can provide these benefits to coastal communities all the time, not just during storm events • In the case of ecosystem restoration, the ecosystem grows stronger with time as it gets established • Has the potential to self-recover after a storm or forcing event • Can keep pace with sea-level rise • Can be cheaper to construct • Can survive smaller storms with less damage than built infrastructure, and can self-repair 	<ul style="list-style-type: none"> • Need to develop best practices for how to restore ecosystems • Provides variable levels of coastal protection (non-linearity of the provisioning of coastal protection benefits) depending on the ecosystem, geography and also on the type and severity of storm; need more research to better understand how to estimate or predict the coastal protection provided • In the case of restored ecosystems, it can take a long time for ecosystems to get established for the natural systems to provide the necessary level of coastal protection • Likely requires a substantial amount of space to implement natural approaches (such as ecosystem restoration or protection of existing ecosystems) which may not be possible • Few data on the cost to benefit ratio for projects • Permitting for natural projects can be a more difficult process than for built projects • Growing but still limited expertise in the coastal planning and development community on which approaches to use where and when
Hybrid (combination of built and natural)	<ul style="list-style-type: none"> • Capitalizes on best characteristics of built and natural • Allows for innovation in designing coastal protection systems • Provides some co-benefits besides coastal protection • Can provide a greater level of confidence than natural approaches alone • Can be used in areas where there is little space to implement natural approaches alone 	<ul style="list-style-type: none"> • Little data on how well these systems perform to date • Does not provide all the same benefits that natural systems provide • Need more research to design the best hybrid systems • Growing but still limited expertise in the coastal planning and development community on which approaches to use where and when • Hybrid systems, due to the built part of them, can still have some negative impacts on species diversity • Few data on the cost to benefit ratio for projects • Permitting for hybrid projects can be a more difficult process than for built projects

understood and has been used in coastal protection for decades. There are many advantages to built infrastructure in protecting communities, but its effectiveness declines over time and it does not have the capacity to adapt to changing coastal conditions. Built infrastructure is strong immediately upon its completion, but it has a set lifetime, weakens with age, and is constructed to specific parameters that cannot adapt to changing sea levels or other conditions. Although built coastal defense structures can help protect communities from the effects of major storms, traditional engineered structures also can have negative impacts on coastal shoreline development, changing the transportation of sediment and the ability of the shoreline to respond naturally to changing conditions and forcing factors, which can result in habitat loss and loss of species diversity (Bilkovic and Mitchell, 2013; Douglass and Pickel, 1999; Govarets and Lauwerts, 2009; Seitz et al., 2006). Another drawback of built structures, such as large seawalls, is that they can lull communities behind them into a sense of false security. This can have devastating impacts if these structures fail during a natural disaster, such as during the Japanese tsunami of 2011 (Onishi, 2011; Parker, 2011). This also is a social risk for communities that choose to make significant investments in built infrastructure; it is critical that people do not develop a complacent attitude toward coastal hazards believing they are protected from all disasters.

There is a great deal of evidence that natural infrastructure provides significant benefits to people (Barbier et al., 2011), not only from direct harvesting of natural goods (e.g., fish, timber) and recreational opportunities, but also including important protection and risk reduction benefits to those living in coastal areas (Arkema et al., 2013; Barbier et al., 2011; Ferrario et al., 2014; Gedan et al., 2011; Rodríguez et al., 2014; Shepard et al., 2011; Zhang et al., 2012). Two comprehensive reviews on natural infrastructure determined that coastal salt marsh vegetation plays a critical role in attenuating waves, providing storm protection and stabilizing shorelines by reducing erosion (Gedan et al., 2011; Shepard et al., 2012). Another recent study examined the wave reduction benefits and the erosional protection benefits of salt marsh under storm surge conditions and determined that the vegetation is responsible for 60% of the wave attenuation during storm events, and that even when waves were large enough to break salt marsh vegetation stems, the plants protected the soil from eroding during major storm events (Möller et al., 2014). Gittman et al. (2014) determined that Hurricane Irene, a Category 1 storm, damaged 76% of bulkheads where the storm came ashore with the strongest winds. At the same time, Irene had no impact on surface elevation of the marshes in the area. This was true whether or not the marshes included built sills – a hybrid shoreline protection structure built of oyster shell or granite on the seaward side of a marsh. Furthermore, the temporary reductions in marsh vegetation density recovered to pre-storm levels within one year. These results suggest that for smaller hurricanes and also for larger storm events, natural or hybrid infrastructure protect shorelines from erosion very effectively and may be more durable (Gittman et al., 2014; Möller et al., 2014).

Several recent studies in mangroves have determined that vegetation structure and species composition are key for

storm protection benefits (Bayas et al., 2011; Tanaka et al., 2007). Mangroves have been shown to be especially good at providing protection from tsunami damage largely due to their complex aerial root structure, which proved to reduce wave damage while trapping manmade debris, lessening impacts to communities behind forests (Bayas et al., 2011). Synthesizing the results of these studies, the ecological factors that generally affect the amount of wave reduction that can be expected from coastal wetlands and mangroves include: the size of the ecosystem, the vegetation density and stiffness (which contribute to an understanding of surface roughness or the frictional resistance), and plant biomass production (Resio and Westerink, 2008; Sheng et al., 2012; Shepard et al., 2011; Zhang et al., 2012). The larger the area of continuous ecosystem, the more coastal protection it can provide. However, even narrow bands of coastal wetlands can significantly reduce wave heights, as can coral reefs (Ferrario et al., 2014; Gedan et al., 2011).

In addition to marshes and mangroves, recent evidence demonstrates the important role of a wide variety of other coastal ecosystems in providing storm and erosion protection, including coral and oyster reefs (Ferrario et al., 2014; Rodríguez et al., 2014), as well as sand beaches, dunes, and barrier islands (Hanley et al., 2014; Spalding et al., 2014). Ecological factors that affect the amount of wave reduction that can be expected from reef ecosystems include reef depth and reef crest height, which are critical to wave reduction in coral reefs (Ferrario et al., 2014) and likely in oyster reefs as well (see Spalding et al. (2014) for a detailed list of both the abiotic and biotic variables that can impact the coastal protection function of ecosystems.)

Several unique strengths of natural infrastructure are that it can be self-maintaining (Gedan et al., 2011), has the potential to self-repair after major damaging events (Ferrario et al., 2014), and has the ability to grow and keep pace with sea level rise – a key consideration as we seek resilience to both episodic and chronic impacts. For example, oyster reefs have recently been shown to be able to grow in height at least as quickly as would be needed to keep pace with predicted sea level rise through 2100 (Rodríguez et al., 2014). An additional benefit of natural infrastructure is that it can sometimes perform the same functions of gray infrastructure but can be cheaper to build and maintain (Gittman et al., 2014; O'Meara et al., 2012; The Nature Conservancy et al., 2013a), although additional efforts to quantify the expected benefits and costs of building and maintaining natural infrastructure would greatly assist policy efforts to incorporate more of these approaches in coastal planning and decision-making (Barbier, 2014).

However, one of the challenges of using natural infrastructure for coastal protection is that ecological parameters are not the only factors affecting the amount of storm protection it can provide. The type of storm can also affect the wave reduction potential of natural ecosystems. Natural ecosystems tend to reduce wave energy better for faster moving storms. During slow-moving storms with prolonged winds, storm surge has a chance to accumulate for longer periods of time, pushing water through the vegetation to the ecosystems or human communities located behind them (Sheng et al., 2012; Zhang et al., 2012). Thus for slower moving storms, vegetation provides some wave reduction but is less effective in reducing storm surge. During Hurricane Wilma, a

Category 3 storm in 2005, a mangrove zone measuring 7–8 km in the Everglades decreased wave heights by 72–86%, largely protecting the freshwater ecosystems behind them, based on a post-storm analysis (Zhang et al., 2012). However, during a slow moving storm, winds would have time to push salt water through the mangroves to the freshwater ecosystems behind (Zhang et al., 2012). This means that planning for coastal protection using natural infrastructure can be more challenging because the variability in the coastal protection benefits provided depends on many ecological and storm-specific factors.

3.3. Research needs: a need for technical and social analysis of coastal protection benefits

Better understanding how natural infrastructure approaches perform during extreme events is key to assessing overall coastal resilience. Though we did not set out initially in this study to develop a list of research needs, as we synthesized the available research we discovered that there were some key gaps or questions that need to be addressed. Thus, determining and highlighting the main gaps in research became more of a focus of our efforts, as filling these research gaps will help improve community policy and decision-making and enhance coastal resilience.

We discovered that there are both natural and social science research gaps where information is lacking in the published literature, some of which have been identified in other studies and some of which we identified. In terms of the priorities for natural science research, these include more information on the level of protection provided by different types of natural infrastructure (i.e., different ecosystems), how that protection varies across different geographic regions and through time, and under what conditions natural infrastructure is likely to fail (Ferrario et al., 2014). Specifically, field experiments are needed to understand: (1) how natural infrastructure handles extreme events since most of the data available are only for smaller storm events with waves smaller than one meter (Bouma et al., 2014; Shepard et al., 2011; van Slobbe et al., 2013); (2) how these benefits vary with different types of storms (fast or slow moving (speed), and different intensities, durations, tracks, and sizes of storms, which all contribute to the amount of storm surge generated) as well as with surrounding coastal landscape parameters including bathymetry, topography, and shelf width (Resio and Westerink, 2008; Wamsley et al., 2010), and affect the long-term resilience of coastal ecosystems, particularly in the face of climate change (Bouma et al., 2014); and (3) non-linearity in the provision of services, such as seasonality, which in many regions affects biomass (Koch et al., 2009). We also need to develop best practices for restoring or constructing natural and hybrid infrastructure that combine our knowledge of the state of engineering and ecological science of coastal ecosystems, particularly with a focus on how to design systems for hazards and disaster reduction (Ferrario et al., 2014).

At the same time, the following social science questions are key to understand: (1) the value (monetary or non-monetary) of storm protection services (although there are a few studies on the value of storm protection (see Section 3.1) there are not

very many and they tend to use different methods for determining the value of storm protection benefits); (2) the value of all the co-benefits natural infrastructure provides (see Barbier et al., 2011, but note there within that many categories of ecosystem services have no determined value to date); and (3) the trade-offs society needs to consider and is willing to make for coastal protection versus other uses such as coastal development opportunities. Identifying, measuring, and quantifying services, and sometimes simply clarifying that a service is being provided, is important. It is also important to note that while it is not necessarily critical to monetize a service in order to include it in a decision-making context, it is critical to recognize that a service is being provided. Without this recognition, the value of these services is zero by default because they are not included in decision-making frameworks. We thus undervalue these ecosystems greatly because we do not account for the multiple benefits they provide to people (Das and Crepin, 2013) in cost-benefit analyses and other decision-support tools. In fact, a recent recommendation from a panel of experts at the National Academy of Sciences suggested that to improve coastal resilience, we need to make sure that all (or at least most) costs and benefits of projects, including social and environmental costs and benefits, are included in order to support better coastal management decisions (National Research Council of the National Academies et al., 2014). These data are critical to inform decision-making, including in land use and coastal zone management, building codes, insurance rates, and hazard and restoration planning.

In recognition of the need for additional analysis, the Hurricane Sandy Rebuilding Strategy included a set of recommendations focused on developing consistent approaches to valuing the benefits of natural infrastructure and developing tools, data, and best practices to advance the broad integration of natural infrastructure (Hurricane Sandy Rebuilding Task Force, 2014). This work spurred additional federal efforts to review existing literature, identify knowledge gaps related to the valuation of coastal green infrastructure (natural or nature-based infrastructure), and develop actionable recommendations for research and data collection priorities across federal agencies, which will be released in Spring 2015.

4. Innovation in natural and hybrid infrastructure

Moving forward, one of the most exciting parts about increased interest in using natural or hybrid approaches is that there is a great opportunity for innovation, particularly related to hybrid approaches where natural and built infrastructure are combined to provide maximum storm protection benefits (Gedan et al., 2011). Because built and natural infrastructure have different strengths and weaknesses (Table 1), using a combination of these approaches can capitalize on the strengths of both while aiming to minimize the weaknesses of each. For example, coastal ecosystems are already one of the most threatened ecosystems in the world due to human impacts (Pendleton et al., 2012), with loss rates ranging from 0.7 to 7% every year (McLeod et al., 2011). Coastal

ecosystem restoration is a key strategy for increasing natural coastal defenses and coastal resilience, but newly constructed or restored natural infrastructure can be weak as organisms take hold. However, these approaches will grow stronger with time as long as the ecosystems are protected from major storms or other stressors as they mature. As a result, there may be opportunities to use engineered structures, such as removable seawalls (Fig. 2), to temporarily reduce disturbances and protect natural infrastructure in its early stages (Bouma et al., 2014). This hybrid approach could help communities use natural infrastructure with more confidence since built infrastructure can provide coastal protection benefits in the interim while natural infrastructure establishes.

Similarly, there is also the potential to use natural infrastructure to protect built infrastructure, lessening the impacts of storm energy on built infrastructure. For example, in the United Kingdom some communities are moving built defenses back away from the shoreline and allowing natural infrastructure to develop in front to protect the built infrastructure; this approach, managed realignment, is seen as a cost-effective and sustainable way to deal with sea level rise (Fig. 1) (van Slobbe et al., 2013). Post-Sandy, some coastal communities, such as Howard Beach, Queens, NY, are considering both natural approaches such as berms, salt marsh restoration, rock groins, and oyster restoration along shorelines, as well as hybrid approaches that combine several of the mentioned natural features with built approaches, such as removable flood walls or moveable flood gates that are only used when a storm is approaching. An analysis by The Nature Conservancy suggested that the natural features alone would not likely be able to adequately protect the urbanized community in Howard Beach from major flood events but that a hybrid approach using natural and built features could be a cost-effective solution for reducing flood risk (Freed et al., 2013).

Another example of a hybrid approach that has been very effective is “living shorelines,” which typically uses a combination of habitat creation or restoration and built infrastructure to provide protection from erosion and storms while also providing some of the benefits of natural habitats. This approach has a great deal of support in several states including Maryland, which passed the Living Shorelines Protection Act in 2008, but also in Virginia, North Carolina, New Jersey, New York, Connecticut, Rhode Island, and Mississippi.

In particular, highly urbanized coastal cities also are looking for creative, hybrid approaches to flood protection because they often do not have the space to implement only natural infrastructure approaches. For example, funded by the Sandy Supplemental, and led by the Department of Housing and Urban Development (HUD), Rebuild by Design was an extraordinary competition launched in 2013 that, through an intensely collaborative process, created proposals to build innovative and resilient infrastructure projects in the Sandy-affected area by using both public and private resources (Rebuild by Design, 2014). In the spring of 2014, ten teams comprised of designers, architects, landscape architects, water-experts, engineers, scientists, and academics from all over the world showcased their final designs. Rebuild by

Design set a new standard for large-scale disaster response and infrastructure projects – the competition was named as the first of the Cable News Network’s (CNN) top 10 innovative ideas of 2013. The core of Rebuild by Design’s tactics was the high level of community engagement and partnership. All ten teams engaged coalitions of local stakeholders in the Sandy-affected area, including residents, nonprofit organizations, business owners, government, and elected officials, which gave them a detailed understanding of the community’s needs and vulnerabilities. This nurtured a heightened awareness of climate change among community members and stakeholders and developed their capacity to take a more hands-on role in advocating for and creating resilient responses to natural disasters. In June 2014, the HUD Secretary announced the winning competition proposals together with the corresponding awards of funding to assist in implementation. A total of \$930 million was awarded to State and local governments for six winning proposals and one finalist proposal (Hurricane Sandy Rebuilding Task Force, 2014). Each of the winning proposals is planning a significant hybrid infrastructure component, and could be closely monitored in years to come to further prove the benefits of these approaches in strengthening coastal protection and improving quality of life. In addition, although only six projects were selected for funding in New York and New Jersey (see winners at <http://www.rebuildbydesign.org/winners-and-finalists/>), a conversation among experts and the community was engendered across all ten project proposals and corresponding areas – including in Connecticut. It is too early to tell what the impacts from this shift in conversation and thinking will be, but we expect these tailored conversations and approaches to continue to pay dividends toward enhancing resilience.

New York City has further developed its own plan called PlaNYC, which includes many innovative areas of research and potential implementation. The city recently released a research plan to study the use of hybrid approaches in protecting much of New York City from erosion and flooding. The Coastal Green Infrastructure Research Plan for NYC identifies and assesses six coastal infrastructure strategies to provide protection and enhance resilience to hazards, while also providing a suite of co-benefits. The six approaches include: constructed wetlands and maritime forests; constructed reefs; constructed breakwater islands; channel shallowing; ecologically enhanced bulkheads and revetments; and living shorelines (Zhao et al., 2014). The plan prioritizes research needs moving forward as it aims to aid decision-makers in evaluating strategies to protect the city and harbor.

Boston, Massachusetts, also has been aggressively researching options to protect the city post-Sandy as part of its “Designing with Water” efforts (see many great examples in Aiken et al., 2014). Boston has discovered different examples of hybrid approaches that could be used to make the city more resilient to climate change and storms including by learning from the Dutch “Living with Water” efforts (Kazmierczak and Carter, 2010), where the Dutch are working to make room for flood waters in urban settings and building floating communities for flood control and socioeconomic prosperity. Boston has itself just completed a competition called “Living With Water” (<http://www.bostonlivingwithwater.org/>), which was an international call for design solutions envisioning a more

resilient, more sustainable, and more beautiful Boston prepared for sea level rise and conditions at the end of the 21st century. Successful projects needed to help build resilience to disturbances both for existing built infrastructure as well as for community and social networks, and do “double duty” in terms of providing protection in times of need but also providing other benefits and uses (such as recreational opportunities) when storm protection is not needed.

Another fascinating hybrid example is the Cheonggyecheon stream restoration in Seoul, Korea, which involved taking out a major highway and putting in a restored stream to provide protection from a 200-year storm event during the rainy season, but which also provides recreational opportunities during the dry season and has resulted in land values increasing in the surrounding area by 30–50% (Landscape Architecture Foundation, 2014).

One of the most challenging parts of working with hybrid approaches is that most have been built very recently, which means that in many cases there are few data on their effectiveness or on the cost to benefit ratio. Yet, hybrid approaches are growing in number with a diversity of approaches providing exciting new opportunities for cities and communities to plan for and adapt to changing sea levels while reaping co-benefits like recreational opportunities and greener urban living options. However, it is important to recognize that hybrid systems may not provide all the same benefits of natural infrastructure. For example, hybrid systems may provide less habitat and support less species diversity than natural infrastructure (Bilkovic and Mitchell, 2013; Seitz et al., 2006). Nevertheless, careful design of hybrid approaches can provide enhanced coastal protection (Gittman et al., 2014) while still providing a number of ecosystem services such as water quality enhancement (Bilkovic and Mitchell, 2013). Thus, a hybrid approach may be preferred over a built approach because it will provide some co-benefits even if a hybrid approach is unable to provide all the co-benefits that a natural approach might.

Another possible innovative opportunity in coastal development and redevelopment is the ability to use designs inspired by nature to enhance the benefits provided by traditional built infrastructure. Such designs can mimic natural habitat to provide more coastal and marine ecosystem services. For example, adding rock pools to seawalls that mimic intertidal habitat can provide additional benefits, including supporting marine biodiversity, so that defense structures can achieve multiple benefits in addition to storm protection (Browne and Chapman, 2014; Firth et al., 2014).

5. Limitations and challenges to using hybrid and natural approaches

It is important to recognize that there can be some unique challenges or constraints when using natural and hybrid approaches. For example, one current challenge with implementing living shorelines is that permitting for these projects can take much longer than a permit for built infrastructure such as a bulk head because living shorelines projects often have to apply for an individual Clean Water Act 404 permit, while bulkheads can often be covered under an Army Corps

Nation Wide Permit (which are generally granted more quickly). This is a policy challenge that some states are addressing by attempting to streamline the process for permitting living shorelines projects, but this does still pose issues for hybrid approaches versus traditional built approaches.

Additional challenges include a lack of data for informing cost benefit analysis (CBA) studies where built infrastructure options are compared to natural or hybrid options. Because there are usually data available for built options on the cost of construction and the anticipated benefits, but similar data for natural or hybrid options are often lacking, comparisons of the two options are difficult (Committee on U.S. Army Corps of Engineers Water Resources Science et al., 2014). Further, while there are generally more and better data on the protective services provided by salt marshes, mangroves, and reefs than on those provided by seagrasses, beaches, and dunes (Barbier et al., 2011; Kroeger, 2012), there is substantial regional variation in the nature and quality of ecosystem service data available, which in turn leads to substantial variation in ecosystem service valuation estimates across different regions. There is also a lack of data on the negative costs of built options (such as the decreases in biodiversity or the increased erosion where built infrastructure ends) so the negative costs of built infrastructure are often not included in CBA for built infrastructure, which can artificially inflate the positive impacts of built infrastructure since the negative costs are not fully incorporated.

Another challenge is the lack of space for implementing natural and hybrid approaches in many urbanized areas. Due to development and hardened, impervious surfaces (such as roads), flood protection measures, or steep gradients in topography, many coastal ecosystems are limited in their ability to migrate inland as sea levels rise. This phenomenon is called “coastal squeeze” and will result in the eventual drowning of some coastal habitats if they cannot move inland with rising water levels (Pontee, 2013). However, even roads and other infrastructure do not pose a permanent problem if there is enough will to change. Many cities are considering or even implementing major infrastructure projects and removing key infrastructure, like major highways or housing developments, in order to create the space for natural infrastructure. Such was the case in the Cheonggyecheon stream restoration in Seoul, Korea, described above. This challenge can be overcome with enough public will and with enough funding for projects.

An additional challenge is the lack of expertise in the coastal development and community planning on the use of natural and hybrid infrastructure since these methods are newer and not as well tested or as well-known as more traditional built approaches. This challenge can, and in some cases already is, be overcome as demonstrated by major cities, such as New York, NY and Boston, MA, where there have been recent, impressive efforts to think creatively about how to protect communities from extreme events and how to better “design with water” (Aiken et al., 2014), for example.

As natural and hybrid approaches gain momentum around the globe, there likely will still be a need for more traditional built infrastructure. However, the use of built structures, such as seawalls, may start to be challenged by some communities

that do not want to lose their connection with the ocean and prefer to find solutions that include the co-benefits provided by natural or hybrid approaches. For example, in post-tsunami Japan, government plans for extensive rebuilding and expansion of seawalls along the northeastern side of the island has spurred high-level international discussion on which approaches – concrete, natural, or a mix of the two – are necessary to secure coastal resilience (R3ADY Asia-Pacific, 2015). These discussions are not without their controversy. In some areas, the height and length of planned seawalls will be quite large, such that coastal communities will no longer be connected to the ocean. Some communities are at odds or are in disagreement with this approach (Bird, 2013; Euronews, 2013).

Because there is no one size fits all solution for improving coastal resilience, many strategies are needed to improve coastal resilience, including the examples presented above for developing improved natural and hybrid coastal protection systems. Moving forward, we need to facilitate implementation of natural and hybrid approaches, and to support more innovation as well as planned and monitored field experimentation as we develop a better sense of which approaches work best in different locations and under different circumstances.

6. Conclusions

Now, before the next big storm, is the time to develop regional and national strategies for coastal risk reduction that include a greater focus on natural and innovative hybrid infrastructure, in combination with appropriate built infrastructure where necessary. The research suggested here provides a foundation of information necessary to support the inclusion of natural and hybrid approaches in coastal planning and policies, and to motivate greater focus on assessing the benefits of these approaches. As we gain more information, the scientific research findings can be combined with policy changes at all levels to enable their success, including changes in zoning, land use, and building codes. More informed decisions for the long-term resilience of coasts will be possible if we incorporate the benefits derived from natural and hybrid infrastructure into decision-support tools, associated training and technical assistance, as well as policy and planning measures, such as coastal zoning and restoration planning. Some communities are already implementing natural and hybrid approaches. We can build on these early successes and develop a more robust and widespread use of natural and hybrid infrastructure. Now is the time to design, test, research, develop and apply the most effective natural and hybrid infrastructure solutions for protecting our communities and strengthening coastal resilience.

7. One sentence summary

Natural infrastructure (i.e., healthy ecosystems) and combinations of natural and built infrastructure (“hybrid” approaches) can provide important storm protection and other benefits to coastal communities, thus more research and

investment in, and application of, natural and hybrid approaches need to be included in coastal resilience planning and decision-making at all levels.

Acknowledgments

We thank Keelin Kuipers, Kim Penn, Carol Kavanagh, and Paul Sandifer for very helpful feedback on this manuscript. We thank Kristen Crossett for help with the figures and Micah Effron and Emory Wellman for help with some of the literature search. Janine Harris provided very useful information on living shorelines. Dr. Sutton-Grier was partially supported by NOAA grant NA14NES4320003 (Cooperative Institute for Climate and Satellites – CICS) at the University of Maryland/ESSIC. The results and conclusions, as well as any views or opinions expressed herein, are those of the authors and do not necessarily reflect the views of the National Oceanic and Atmospheric Administration (NOAA) or the U.S. Department of Commerce. This publication does not constitute an endorsement of any commercial product or intend to be an opinion beyond scientific or other results obtained by NOAA.

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