Performance of Natural Infrastructure and Nature-based Measures as Coastal Risk Reduction Features

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Introduction

The Environmental Defense Fund (EDF) aims to improve the ability of coastal communities to reduce risks from sea level rise and coastal storms through the use of natural infrastructure and nature-based measures.

Recognizing that better quantification of the storm risk reduction benefits of these approaches is necessary to help decision-makers choose among alternatives to protect their communities, as well as help to develop new market-based or private sector funding options for natural infrastructure and nature-based measures, this paper presents a review of the state of knowledge on the performance of these approaches, compiled from existing literature and participant input obtained during an EDF-convened expert workshop in May 2015.

This EDF report represents the review of the state of knowledge on the performance of natural and nature-based infrastructure as compiled from existing literature and participant input obtained during an expert workshop. Table 1 provides an accessible summary of the most current state of understanding of the risk reduction performance of natural infrastructure. It is important to note that, while absent from the Table 1, non-structural approaches, such as zoning, building codes and evacuation planning, play critical roles in increasing coastal resilience. Sutton-Grier et al. (2015) highlight the strength and weaknesses of the coastal protection benefits provided by traditional built infrastructure, natural ecosystems, and combinations of built and natural infrastructure solutions. Improved resiliency to coastal storms requires careful consideration of this full suite of tools.

Background and Methods

In May 2015, EDF brought together nineteen scientists, engineers, program managers, and financiers for a workshop to discuss establishing disaster risk reduction and climate adaptation performance of natural infrastructure and nature-based measures for coastal communities. See Table 2 for a list of participants. EDF's goals for the workshop were to:

- Inform EDF's plans to advance the effective use of natural infrastructure and nature-based solutions in reducing risks from coastal storms and sea level rise; and
- Connect decision-makers with the research community to encourage an exchange about current knowledge, as well as identify where additional research is needed, about the performance of natural infrastructure and nature-based measures.

Prior to the workshop EDF developed and provided to invited workshop participants a draft of Table 1 and a literature review regarding the performance of the following natural and nature-based measures. The literature review focused on the risk reduction performance, including attention to uncertainties regarding each measure's ability to keep pace with anticipated sea level rise and mitigate climate change by sequestering carbon. The review also identified outstanding research questions. EDF asked workshop participants to provide input to expand, amend or otherwise refine the literature review and summary table.

Over the course of the workshop, EDF asked participants to identify the kinds of information needed to establish the risk reduction performance of natural infrastructure and nature-based measures and the conditions affecting their reliability. EDF also asked workshop participants to identify other opportunities and challenges to scaling up each measure's adoption, including research needs to develop, refine, or improve understanding of risk reduction performance and development of design criteria as well as policy and practice needs. Participants were asked to identify and prioritize research needs based on which were most pressing or would catalyze broader and more rapid acceptance of natural infrastructure and nature-based measures.

Following the workshop, EDF supplemented the literature review with key points raised during workshop discussions. Items lacking citations represent the oral communications of workshop participants.

EDF provided workshop participants, and other external experts[1], a revised literature review for additional comment. This final version represents EDF's incorporation of those additional comments.

Findings

BEACH NOURISHMENT

Methods of risk reduction

- Breaking of offshore waves. (USACE, 2013)
- Attenuation of wave energy. (USACE, 2013)
- Beaches, when combined with sand dunes, reduce the risks of storm surge–related wave attack and flooding on barrier islands and the mainland. (NRC, 2014)

Method strengths

- Reduces erosion, flooding, and wave attack and may reduce the likelihood of forming new inlets. (NRC, 2014)
- An increase in the sediment budget downdrift of fill areas enhances the likelihood for landforms to evolve, increasing topographic diversity in a way that is more natural than by direct nourishment. (NRC, 2014)
- Beachfill might protect not only the beach where it is placed, but also downdrift stretches by providing an updrift point source of sand. (USACE, 2006)
- Coastal risk reduction projects can be designed to provide increased ecological value. (NRC, 2014)

Known weaknesses

- Requires periodic to continual sand resources for renourishment.
- Can be eroded by extreme event surge and waves; no high water protection.
- Possible impacts to regional sediment transport.
- Can lead to removal of large volumes of offshore sand. (NRC, 2014)
- Does not address back-bay flooding. (NRC, 2014)
- Even though beach nourishment is generally considered as an environment-friendly option for coastal protection and beach restoration, sizeable impacts on several beach ecosystem components (microphytobenthos, vascular plants, terrestrial arthropods,

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[1] The additional external experts are listed in Table 2.

marine zoobenthos and avifauna) can occur. (Speybroeck et al., 2006) The projects may may cause undesirable side effects, including ecological impacts on offshore dredging sites and unnatural sand/sediment types at project sites.

- Can lead to steeper beach profiles, which can increase wave energy on the beach, increase beachside erosion, and preclude wave overwash. (Green, 2002)
- The lifetime of beach nourishment projects are often short, and beaches may need to be re-nourished frequently.

Uncertainties about utility for risk reduction & resilience

- The level of risk reduction afforded by a beach nourishment project varies over time, as the beach and dune are eroded by natural processes, requiring periodic renourishment (varying by location). (NRC, 2014)
- Unpredictable lifetime: storm history is the most important factor in determining beach durability. Beach length, grain size, shoreface slope, shelf width and method of fill emplacement show no correlation to regional replenished beach lifetime. (Leonard et al., 1990)
- Erosional hot spots may develop from a variety of causes, including material source and the presence of adjacent structural measures. (Kraus and Galgano, 2001)
- There are several recognized failure modes for beach fills (USACE, 2006):
    - Failure to protect upland property or structures during storm events.
    - Movement of fill material to undesired locations, such as into inlets or harbors.
    - Loss of fill material at a rate greater than anticipated for some reason other than design wave exceedance.

Suitable Conditions

- Most:
    - Low-lying oceanfront areas with existing sources of sand and sediment.
- Least:
    - Not generally well-suited for application to most major urban centers or areas with large port and harbor facilities because of the space requirements and the level of risk reduction desired. (NRC, 2014)
    - Not suited where no local source of beach fill exists.

Performance factors/Performance evaluation metrics/Design metrics

- Part of the design process is estimating how long the beach fill will serve its function under typical wave conditions. (USACE, 2006)
    - Such estimates are difficult, at best, because of wave climate uncertainty and the complexity of beach fill response to storm conditions. (USACE, 2006)
    - A new project may suffer a severe storm immediately upon completion, resulting in massive fill losses, or the beach fill may serve for many years without ever being exposed to design storm conditions. (USACE, 2006)
- Beach slope. (USACE, 2013)
- Beach width.
- Storm berm.
- Sediment grain size and supply. (USACE, 2013)

- Improvements for ecological benefits of beach nourishment and dune construction would involve different design specifications that are unlikely to greatly increase construction costs, although they may require alternative approaches to post-construction beach and dune management. (NRC, 2014)

Capacity/Limitations of method to keep pace with climate change

- Requires a natural sediment source or constant maintenance to grow, add elevation.
- Often natural sediment sources are cutoff or significantly reduced by anthropogenic change

Examples of sites where implemented

- All US coasts have examples. A comprehensive data base of beach projects in the United States can be found at http://beachnourishment.wcu.edu.
- Sand motor – Netherlands, South Holland.

Most catalytic/pressing research needs

- What are the impacts on borrow sites (on wave and current behavior)?
  - What are the ecological and coastal impacts of dredging?
- What is the impact of beach nourishment on localized currents and the beach recolonization/recovery period?
- What is the effectiveness and what are the impacts of sand motors?

Additional research needs

- What is the impact of beach management practices on aeolian processes, dune building and beach stability?

See Atlantic States Marine Fisheries Commission report, "Beach Nourishment: A Review of the Biological and Physical Impacts" (Green, 2002)(p. 36 for a thorough list of additional research needs).

VEGETATED DUNES

Methods of risk reduction

- Breaking of offshore waves. (USACE, 2013)
- Attenuation of wave energy. (USACE, 2013)
- Act as barriers against waves, currents, storm surges and tsunamis. (Renaud et al., 2013 (page 34) citing IOC, 2009, UNEP- WCMD, 2006)
- Reduce washover currents. (Morton and Paine, 1985) (in Morton, 2002)
- Reduce wind speed. (Powell and Huston, 1996) (in Morton, 2002)

Method strengths

- Dunes with vegetation perform more efficiently, ensuring stability, greater energy dissipation, and resistance to erosion. (NRC, 2014)
- Methods of predicting levels of storm protection provided by beaches and dunes exist. (Hallermeier, 1987) (in Nordstrom et al., 2011).

- Dunes constructed on barrier islands could reduce the possibility for overwash or breaching, potentially lessening the likelihood of bay flooding. (NRC, 2014)

Known weaknesses

- Not well suited for major urban centers or large port/harbor facilities because of space requirements and the level of risk reduction required. (NRC, 2014)
- Building "unnaturally high dunes on barrier islands" that protect against overwash "prevent natural accretion processes that help sustain the island itself." (Maslo et al., 2011; Schuup et al. 2013) *(*in NRC, 2014)
- Artificial dunes do not necessarily respond the same way to storm processes as natural dunes. (Morton et al., 1994) (in Morton, 2002)
    - Even when indigenous species are planted on artificial dunes, the roots may remain shallow because the plants did not grow while the dunes aggraded. Consequently, artificial dunes can be less resistant to wave attack and erosion than natural dunes, and as a result they may erode more rapidly than natural dunes. (Morton et al., 1994)
      (in Morton, 2002)
- High vegetated dunes can preclude the penetration of storm surge, and simultaneously divert the high-velocity flow into adjacent low-lying areas that become washover conduits. (Wright et al., 1970; Kahn and Roberts, 1982) (in Morton, 2002)

Uncertainties about utility for risk reduction & resilience

- Regional distinctions in beach and dune characteristic result in different susceptibility to overwash and flooding, even under same storm wave and surge characteristics. (Sallenger, 2000)
- Many design considerations for providing optimum protection have yet to be worked out. (Hanson et al., 2010) (in Nordstrom et al., 2011).
- Little is known about how the initial dimensions and subsequent evolution of vegetated dune designs will affect habitats and how much human action is required to establish and maintain them. (Nordstrom et al., 2011)
- Reduction of risk in one area can lead to increased risk in other areas.

Conditions where most/least suitable

- Most:
    - Wide beaches, high dunes (beaches with natural or local sediment sources of similar size and composition).
    - Where new development close to the backshore can be prevented, where the beach has a positive sediment budget, or where beach fill is used to overcome restrictions in sediment availability. (Nordstrom et al., 2012)
    - Large and most medium-sized dunes survived storms better. (Nordstrom et al., 2000)
    - Small dune forms can exist for longer periods if they are accepted by humans as part of the landscape. (Nordstrom et al., 2000)
    - Protective foredunes can be designed to be large enough to provide protection against storms and thus survive periods of years. (Nordstrom et al., 2000)
    - Dunes of medium size (that would form naturally in the absence of human efforts) would last a few years, but foredunes that are artificially enhanced can last decades. (Nordstrom et al., 2000)

- Least:
    - Areas that would not be naturally sustainable (see the known weaknesses above).

Performance factors/Performance evaluation metrics/Design metrics

- Dune height, crest and width. (USACE, 2013)
    - Trapezoidal/ flat topped dunes more effective than round topped dunes
- Beach slope. (USACE, 2013)
- Sediment grain size and supply. (USACE, 2013)
- Berm height and width. (USACE, 2013)
- Vegetation types; surface and root structures.
- Freshly accumulated wrack and plant growth on the backshore are effective traps for wind-blown sand. (Dugan and Hubbard, 2010)(Nordstrom et al., 2011a)
    - These natural sand traps appear to be important in increasing and maintaining the volume and elevation of the upper backshore and dune of the unmanaged sites. (Nordstrom et al., 2012)

Failure/ Resiliency/Post-storm event recovery factors

- Although a dune may erode during a storm, in many cases it provides a sediment source for beach recovery after a storm passes. (USACE, 2013)
- Under natural conditions, restoring of the morphology and vegetative assemblages of foredunes after storm loss can take up to 10 years. (Maun, 2004; Woodhouse et al., 1977) (in NRC, 2014)
- Nourishing a beach with suitable sediment can create a dune. (Nordstrom et al., 2011)

Capacity/Limitations of method to keep pace with climate change

- Has capacity, if a sediment source is available and the island has the ability to move leeward.
- Islands and spits are prevented from keeping pace with sea level rise or from re-establishing now rare dynamic habitats, such as overwash fans favored by some species. (NRC, 2014, citing Maslo et al. 2011, Schuup et al, 2013)

Examples of sites where implemented

- Multiple sites, all US coast; for example, Avalon, NJ, has both managed and unmanaged dunes.
- NRDA-Trustees (2012) provide an estimate for vegetated dune restoration at Pensacola Beach, Florida.

Most catalytic/pressing research needs

- How can we establish post construction management practices to ensure sediment resources evolve to a condition that provides environmental benefits as well as coastal risk reduction? (Nordstrom et al., 2011)
- What is the contribution of root/vegetation presence on dune function?
    - Do unknowns associated with root/vegetation presence contribute to additional risk/uncertainty?
- What are the roles of inlets? How much benefit do dunes provide in reducing risk of mainland flooding in areas with inlets?
- What is the effect of vegetated vs. non-vegetated dunes on storm surge? Is this quantifiable?
- Dune dynamics :

    - How does a dune's ability to increase coastal resiliency change over time?
    - How does the cost of maintenance change over time?
- What is the role of hybrid natural, nature-based, and structural solutions, such as sea wall buried beneath a sand dune?
- Are there better alternative dune designs/configurations?
- How do morphology, evolution, and duration of landforms differ on raked and unraked beaches? (Nordstrom et al., 2011)
- What are the metrics to best monitor continued risk reduction effectiveness? (Nordstrom et al., 2011)

Additional research needs

- For dune restoration suitability in developed areas:
    - How can aeolian transport and dune mobility be accommodated without significantly increasing the degree of sand inundation? (Nordstrom et al., 2011)
    - Will topographic variations lead to formation of blowouts and increase likelihood of overwash? (Nordstrom et al., 2011)
    - Does forested/scrubby dune vegetation increase scour and decrease risk reduction performance?
    - Is preservation of the upper litter line sufficient to regenerate useful incipient dune forms? (Nordstrom et al., 2011)
    - What distance alongshore is required for the no-rake zone to ensure the formation and survival of a naturally functioning dune?

BARRIER ISLAND RESTORATION

Methods of risk reduction

- Wave attenuation, and/or dissipation.
    - Hurricane simulations show barrier islands and coastal ridges reduce wave heights, even in a degraded condition. (Wamsley et al., 2009)
- Sediment stabilization. (USACE, 2013)
- More effectively dissipate shorter-period fluctuations, such as wind waves, than long waves, such as tides and storm tide. (Arcadis et al., 2014)
- If a constructed breakwater island successfully mimics a naturally occurring barrier island, there is significant potential to reduce both spring and storm tide water surface elevation. (Arcadis et al., 2014; Renaud et al., 2013)
- Larger islands (e.g., size of Galveston Island) that change flow can provide protection for storm surge (Rego and Li, 2010)
- Barrier island restoration may significantly alter surge pathways and flood volumes of surge reaching inland coastal areas as passes become the dominant flow mechanism during a storm event. (Grzegorzewski et al., 2011)

Method strengths

- Good protection from rising tides/inundation and for dampening waves.
- A natural barrier island system with a sufficient crest height can block and redirect the intrusion of storm surge based on numerical simulations of Hurricane Ike (2008) in Galveston Bay, Texas, for a wide range of barrier system conditions (e.g., existing, eroded, breached, flattened, and submerged). (Rego and Li, 2010)

- Numerical modeling of the Chandeleur Islands in the Mississippi River Delta show increased storm surge with increased barrier island degradation. (Wamsley et al., 2009)

Known weaknesses

- Gradual hazard erosion mitigation and sedimentation is directly tied to barrier island location and shape.
- Comparisons between water levels before and after Hurricane Sandy at bay stations and an offshore station show no significant differences in the transfer of sea level fluctuations from offshore to either bay following Sandy (Aretxabaleta, 2014)

Uncertainties about utility for risk reduction & resilience

- Regional distinctions in beach and dune characteristic result in different susceptibility to overwash and flooding, even under same storm wave and surge characteristics. (Sallenger, 2000)
- Recovery rate, if impacted by multiple storms in short period of time.
- Availability of sediment supply.

Suitable Conditions

- Most:
    - Renewable/sustainable sand supplies, on existing footprints of barrier islands.
- Least:
    - Areas in which barrier islands wouldn't naturally form, are unlikely to naturally form, i.e., rocky coasts, or where there is a natural propensity to migrate landward.

Performance factors/Performance evaluation metrics/Design metrics

- Island size:
    - Island elevation. (USACE, 2013)
    - Island length. (USACE, 2013)
    - Island width. (USACE, 2013)
- Land cover. (USACE, 2013)
- Breach susceptibility. (USACE, 2013)
- Proximity to mainland shore. (USACE, 2013)
- Barrier island effectiveness is limited by its crest elevation and horizontal scale. (Arcadis et al., 2014)
- Dunes on barrier islands could reduce possibility of overwash or breaking, potentially lessening the likelihood of bay flooding. (NRC, 2014)
- Storm size and other storm characteristics that contribute to storm surge elevation and duration. (Some barrier islands did not affect surge levels that occurred during Super Storm Sandy, but would likely have performed for a 50-year event.)
- A wave transmission coefficient (the ratio of wave height offshore to that on the leeward side of the island) is often used to quantify the breakwater performance. (Arcadis et al., 2014)
    - The existing empirical relationships among those parameters developed on the basis of implemented projects and natural landscapes can only be used for initial estimations. (USACE, 2002 in Arcadis et al., 2014)
    - Advanced computer models and physical models allow for more detailed assessments of complicated design of footprints and configurations to understand the impacts of design on both hazard mitigation and ecological benefits. (Arcadis et al., 2014)

- Performance enhanced if restoration includes backbay marsh restoration. (Arcadis, 2013)
- Beach-dune nourishment design and construction templates are available to address implications of use of finer versus coarser sands for nourishment. (Campbell et al., 2005)
- Surrounding coastal landscape; geometry of the adjacent passes and tidal inlets. (Grzegorzewski et al., 2011)

Failure/Resiliency/Post-storm event recovery factors

- The lifespan of islands constructed from dredged material without engineering structures is not yet known, but it can vary significantly depending on where the island is located. (Arcadis et al., 2014)
    - Factors that may affect the sustainability (or failure) of this strategy are, first and foremost, the adaptability of the various habitat and ecosystem types within this strategy and the sediment stability of the strategy. (Arcadis et al., 2014)
    - The littoral sediment supply, the presence of engineered structures to retain nourished sediment, and the geotechnical and geochemical properties of dredged material used for the substrate are critically important. (Arcadis et al., 2014)
- Either insufficient sediment supply or vegetation mortality due to storm or sea-level rise can cause damages to the system and result in collapse of the barrier island. (Arcadis et al., 2014)

Capacity/Limitations of method to keep pace with climate change

- Yes, if overwash can occur (Dolan and Lins, 1986)
- Creating higher barrier islands (>3 – 4 meters) will restrict most overwash events; however, this also means the sources of sediments to its back bay marshes will be reduced and in some cases marshes may not keep pace with relative sea level rise. (Campbell et al., 2005)
- A case study conducted along the New Zealand coast showed that planting vegetation immediately above the restored beach can guide a sustaining beach-vegetation cycle and can promote the self-recovery process. (Berg and Limited, 2007 from (Arcadis et al., 2014))

Examples of sites where implemented

- Fort Pierce Marina, Florida: a constructed breakwater island integrates a series of curved breakwaters and T-groins, which provide sediment nourishment. (Arcadis et al., 2014)
- Barataria basin, Louisiana; Day et al. (2005) provide cost estimates for implementation in Louisiana.

Most catalytic/pressing research needs

- To what extent does barrier island creation reduce inland flooding?
- How far do benefits penetrate inland?
- What is the cost of maintenance over time?
- What are the metrics to best monitor continued risk reduction effectiveness?

Additional research needs

- How do change in the magnitude or frequency of coastal storms impact barrier island resilience? (Houser et al., 2008)

EDGING & SILLS (Living Shorelines of eel grass beds, low sills, sometimes oyster beds)[1]

Methods of risk reduction

- Mitigate erosive waves and stabilize the shoreline.
- The potential protective values are limited to a slight reduction in wave run-up due to the surface roughness (over standard bulkheads and revetment). (Arcadis et al., 2014)
    - The protection values are attributed to the vegetative resistance and the potential presence of a sill. (Arcadis et al., 2014)

Method strengths

- Numerous studies have explored how seagrass canopies modulate water flow and currents (e.g., Fonseca et al., 1982; Gambi et al., 1990), contribute to wave attenuation, and retain and stabilize sediments in shallow coastal areas. (NRC, 2007).
    - Such sediment retention can lead to sediment accretion and reduced water turbidity. (NRC, 2014)
    - Dissipation of wave energy by seagrasses has also been proposed to play a role in reducing erosion of coastlines. (Dean and Bender, 2006; Ozeren and Wren, 2010). (in NRC, 2014)
- Provides ecosystem goods and services, such as recreation, water filtration, and carbon sequestration.
- Tests of oyster bag reefs found comparable results to published methodologies for measuring the wave transmission coefficient for low crested breakwaters. (Allen and Webb, 2011)
- Valuable for smaller scale, higher frequency coastal events.

Known weaknesses

- While effective in minimizing gradual erosion, edging and sills are susceptible to event-based hazards, such as storm surge flooding during extreme storm events.
- Edging and sills offer little to no storm surge flood control due to their typically low crest elevation (e.g., MHHW).
    - Because seagrasses are subtidal, frictional forces would quickly be reduced by higher water levels associated with storm surge. (NRC, 2014)
- Construction of sills and mash can remove sand from the sediment transport system, which may impact proximate shorelines and habitats.

Uncertainties about utility for risk reduction & resilience

- Sea level rise can render some living shorelines ineffective.

Suitable Conditions

- Most:
    - Low energy environments.
    - Suitable in “medium wave environments…where existing marsh is eroding; or where little or no beach is present.” (Burke and Hardaway, unk)

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[1] Small scale living shorelines are typically linear, narrow features placed along the shoreline fringe with a vertical face of sloped surface. Often accompanied by ecologically engineered features that incorporate rough irregular surfaces where organisms can colonize. Often integrate ecologically friendly materials and vegetation.

  - Sills are appropriately used in low or medium energy environments with deeper water depths, from 3-5 ft., where steeper sloping nearshore conditions prohibit marsh establishment without a containment barrier for fill to create suitable gradients for marsh establishment. (Burke and Hardaway, unk)
  - Areas with high erosion rates, above 2ft. per year. (Burke and Hardaway, unk)
  - Because seagrass canopies are relatively short (generally <20 in [50 cm]) and flexible, substantial modification of water flow is most effective when seagrasses are found in high density and distributed over a wide area in shallow water depths. (e.g., Fonseca et al., 1982; Gambi et al., 1990; Christianen et al., 2013).(in NRC, 2014)
  - Higher sills – in front of small headlands or protruding features (Burke and Hardaway, unk)
  - Lower sills – minor indentations and embayments (Burke and Hardaway, unk)
- Least:
  - Areas with ice formation and with significant waves (both wind and boat wakes) were found problematic particularly prior to when vegetation is stable. (Arcadis et al., 2014)
  - Areas where land subsidence and sea level rise are rapidly changing. (Spalding et al., 2014)

Performance factors/Performance evaluation metrics/Design metrics

- Width. (USACE, 2013)
- Elevation. (USACE, 2013)
- Roughness. (USACE, 2013)
- Submerged Aquatic Vegetation elevation and continuity. (USACE, 2013)
- Wave and ice effects on vegetation and structures. (Arcadis et al., 2014)
- Other vegetation type density. (USACE, 2013)
- Sill and window sizing. (Arcadis et al., 2014)
- The quantity of wave reduction depends on the size of the sill, marsh width, marshland vegetation type, and the local wave climate.

Failure/Resiliency/Post-storm event recovery factors

- A sill is subject to the same modes of failure as any other sloping-front structures, such as breakwaters or revetments.
  - If improperly constructed, the finer stones may wash out through the larger voids of the armoring, which could eventually lead to the deflation of the entire structure, lowering the structures' crest and compromising its effectiveness.
- The primary cause of failure is water surface elevations that above the vegetation for long time periods as few wetland plants will survive when fully submerged. (Arcadis et al., 2014)
- Washout of sediment as the floodwater recedes over the wall can also cause significant damage. (Arcadis et al., 2014)

Capacity/Limitations of method to keep pace with climate change

- Unknown, other than what is known about wetlands and other vegetation (Arcadis et al., 2014)
- Limited capability of self-adjusting to sea-level rise. (Arcadis et al., 2014)

- Sea-level rise poses a considerable threat to the success and failure of sills and edging. Where possible, to adapt to rising water levels, the often associated bulkheads and revetments should extend higher in elevation. (Arcadis et al., 2014)
    - A bio wall tied to a bulkhead is not very adaptable to water level or other changing conditions after it has been built. (Arcadis et al., 2014)
- Both joint planting and vegetated geogrids are adaptable to sea level rise in that an additional layer of stakes may be added to reach the desired elevation, until the elevation of the land behind the bullhead is reached. (Arcadis et al., 2014)

Examples of sites where implemented

- Chesapeake Bay and Gulf of Mexico (Arcadis et al., 2014)
- Maryland & Alabama (Arroyo et al., 2013)
- Virginia, North Carolina, Connecticut, Rhode Island (Sutton-Grier et al., 2015)
- Hudson River Estuary (Hudson River Sustainable Shorelines)

Most catalytic/pressing research needs

- How do marsh characteristics (elevation, plant density, width) influence energy dissipation?
- What are the effects of changing sandy shores into sills and marsh?
- Can we create effective living shorelines using just marsh grass? Are sills over-engineered?
- What are the metrics to best monitor continued risk reduction effectiveness?

Additional research needs

- Thresholds for sudden failure. (Spalding et al., 2014)
- Requirements for long-term maintenance, especially where sea level is rising rapidly. (Spalding et al., 2014)
- How successful is a living structure compared to traditional structural strategies? (Arcadis et al., 2014)
- What are the optimum sill dimensions (e.g., sill height, window dimensions, and spacing) for various estuarine/riverine conditions (e.g., channel shape, seasonal flow rates)? (Arcadis et al., 2014)
- How effective are different sill materials (rock, gabions, bulkhead, living reefs) at dissipating waves and holding the front edge? (Arcadis et al., 2014)
- How will sea-level rise impact living shoreline projects? (Arcadis et al., 2014)
- How does ice impact the living elements of living shorelines? (Arcadis et al., 2014)
- What is the stone size and depth of rock cover layer that is necessary for avoiding root wedging?
- To what extent can vegetation stabilize the bank and structure?
- If vegetation becomes overgrown, does it have an adverse effect on the shoreline?
- Can ecologically enhanced concrete and rough concrete surfaces increase the longevity and structural stability of hard coastal structures?
- How are guidelines best improved for the design of coastal structures in icy environments? (Arcadis et al., 2014)
- How does the accumulation of biomass on marine infrastructure affect its maintenance requirements?

- What are the effects on nearby ecosystems of introducing non-native structural controls, such as rocks or oyster shells? (Pilkey et al., 2012)
- Can predominant wind data and other regional factors be used to determine the effectiveness of various methods?
- Can we create an evaluative framework for Living Shoreline performance akin to the USDA's Vegetated Treatment Potential Index?
- Questions remain about long-term benefits, storm response, sedimentation rates, impacts on erosion rates and nutrient contribution, and loss of sandy beach ecosystem. (Pilkey et al., 2012)

OYSTER REEFS *(Nota bene: this information may be applicable to other shellfish dominated structures and calcareous worm reefs)*

Methods of risk reduction

- Dissipate short waves to reduce shoreline erosion. (USACE, 2013)
- Breaking of offshore waves, attenuation of wave energy. (USACE, 2013)
- Combat coastal erosion; enhances shoreline accretion; can increase localized sedimentation (Scyphers, 2011)
- Help protect shorelines by reducing incoming wave energy and marsh erosion. (Marani et al., 2011)

Method strengths

- Fringing reefs can dampen wave energies and increase sediment retention. (NRC, 2014)
- Configured correctly, submerged oyster beds may function as low crested submerged breakwaters. (NRC, 2014)
- Models exist:
    - Due to comparability to submerged breakwaters, can use large data bases and model to evaluate submerged oyster beds and various configurations, under various physical conditions. (NRC, 2014)
    - Three-dimensional numerical models that can resolve the characteristics of pierced reef units are useful to simulate wave propagation and to quantify wave transmission coefficient. (Arcadis et al., 2014)
- Slow erosion and increase local sedimentation but mostly for low to moderate energy events. (Arcadis et al., 2014)

Known weaknesses

- Typically designed with crown elevation at MHHW, therefore quickly overtopped during storms; not effective at dealing with high energy events (higher storm surge and wave heights common in tropical storms). (NRC, 2014)
- Because oyster reefs are similar to submerged breakwaters, not useful for high energy event's wave attack or storm surge flooding. (Taylor and Bushek, 2008)
- Limited to low to medium energy environments with a small to moderate tidal range. (Taylor and Bushek, 2008)
- Along the north Atlantic coast, reefs are highly susceptible to damage from debris, ice, and sometimes longshore shifting sediment. (Taylor and Bushek, 2008)
- Because of the limited horizontal dimensions, low crested reefs, constructed reefs, and high crested hybrid breakwaters and reefs do not provide substantial storm surge

reduction. (Arcadis et al., 2014) supplemented by personal communication from Hugh Roberts (8/19/2015).
- Artificial reefs may lead to increased erosion along the coast.
- Lack of hard data about how different types of oyster reef structures perform. (Stokes et al., 2012)
- Almost universal shortage of oyster shell available for oyster reef restoration projects. (Stokes et al., 2012)
- Areas where ocean acidification is advancing can experience decreased survival of reef systems. (Breitburg et al., 2015)

Uncertainties about utility for risk reduction & resilience

- Limited understanding of the role of healthy ecosystems in reducing hydrometeorological hazards when they become more frequent or extreme or when ecosystems are degraded. (Renaud et al., 2013, p. 450)

Suitable Conditions

- Most:
  - High versatility; can be placed in intertidal and subtidal areas, across a variety of salinities in areas with fine to sandy sediments. (NRC, 2014)
  - Areas with shallow bathymetry.
  - Field trials have shown that oyster larvae will settle on virtually all hard substrates. Significant differences exist, however, in the setting density and subsequent survival of those oyster spat. Irregular surfaces and pore spaces of certain materials (natural oyster shell, stone, crushed concrete, and marl) also protect the oysters from predation. (NOAA, 2015)
- Least:
  - Floating ice - cold air exposure.
  - Areas where ocean acidification impacts could reduce reef viability.

Performance factors/Performance evaluation metrics/Design metrics

- Reef width, elevation, and roughness (USACE, 2013)
- To evaluate the hazard mitigation performance of constructed reefs, a wave transmission coefficient indicating the portion of wave energy transmitted from the unprotected side to the protected side is a common parameter. The relationship of this parameter with traditional breakwater dimensions is developed from model tests and field observations (e.g., the Coastal Engineering Manual (USACE, 2006). (Arcadis et al., 2014)
- The design and placement of breakwaters can be reviewed in the Corps of Engineers' Engineering Manual (EM 1110-2-1100) (USACE, 2006) and its updates which references Seelig (1980) for the estimation of the hydrodynamic properties relating to rubble mound breakwaters. Factors affecting the use of rock in breakwaters are the size, density, shape, and gradation (Poole, 1991). (in Allen and Webb, 2011; van der Meer et al., 2005)
- A high-crest reef (such as might exist with a hybrid breakwater/living reef structure) will be more effective in dissipating wave energy due to its bathymetric and topographic resistance; however, it has been noted that a near-emergent reefs (closer to mean sea level) will be less exposed to intense forces and more likely to survive. (Arcadis et al., 2014)
- The gap along the length of the project between two reefs should not be larger than 2 times the individual reef length and generally is around 2 times the bay indentation. (Arcadis et al., 2014)

    - Bay indentation: the maximum offset of the embayed beach from a line connecting adjacent breakwaters according to the headland breakwater studies (Hardaway and Gunn, 2010 (in Arcadis et al., 2014)).
- The length of uninterrupted reef will have a direct effect on the stability of the overall structure, as well as the level of protection. (Arcadis et al., 2014)
- It is important to maintain integrated reef systems without/minimal fragmentation.

Failure/Resiliency/Post-storm event recovery factors

- A constructed reef is subject to the same physical modes of failure as any other sloping-front structure, such as sill, breakwater, or revetment.

Capacity/Limitations of method to keep pace with climate change

- Capable of keeping pace with sea level rise (Rodriguez et al., 2014)

Sites where implemented

- In Mobile Bay, oyster reefs have been designed to reduce wave heights and energy by 50 percent or more, reducing shoreline erosion and associated damages to private property and public infrastructure. The local economic value of this wave attenuation may be large, based on evidence from other studies that looked at property values and insurance premiums for coastal U.S. areas (Kroeger 2012). (in Arcadis et al., 2014)
- Constructed to protect residential properties located along the banks of small estuaries, e.g., Virginia's Artificial Reef Program (http://mrc.virginia.gov/vsrfdf/reef.shtm).
- Charlotte Harbor, FL.

Most catalytic/pressing research needs

- What are the metrics to best monitor continued risk reduction effectiveness?
- What are quantitative benchmarks for coastal risk reduction performance? (Powers and Boyer, 2014)
- What is the influence of salinity, temperature, turbidity, ocean acidification, etc. on oyster reef environments?
- How can we scale up from information on small reefs to large reef complexes? (Arcadis et al., 2014)
- Interactions between reefs and currents.
    - Effects of longshore/drift current and nearshore currents.
- Expand understanding of wave transmission effectiveness over constructed reefs with various reef unit designs. (Arcadis et al., 2014)
    - What are the wave transmission coefficients? (Arcadis et al., 2014)
- What are the benefits and downsides to the different types of deployment methods?
    - Primary reason for delaying deploying oyster reefs into coastal management plans – "a lack of hard data for how artificial structures perform." (Belhadjali, 2012; Graham, 2011 (in Stokes et al., 2012))

Additional research needs

- Would construction of large-scale reefs in more open water be equally as cost effective as those in a semi-closed environment? (Arcadis et al., 2014)
- If constructed reefs are designed as modified living breakwaters, do the design metrics regarding gaps between two reefs still apply? (Arcadis et al., 2014)
- How does the surface roughness of reefs affect wave transmission? (Arcadis et al., 2014)
- To what extent can oyster reefs work in high energy environments, and can they survive in them? (Arcadis et al., 2014)

- What is the optimal crest elevation, considering structure stability and resiliency? (Arcadis et al., 2014)
- What are possible structural benefits achieved by developing oyster reefs on marine infrastructure (i.e., effect on structural strength, chloride penetration, physical forces absorption)? (Arcadis et al., 2014)
- How can we quantify benefits of different constructed reef substrates, such as live oyster shells, fossilized oyster shells, concrete or crushed limestone, OysterKrete, etc.?
- How do oyster reefs contribute to marsh growth?
- Is it possible to manage the elevation of reef systems without destroying the reef ecosystem?
- Examine the role of other types of biological reef systems:
    - Likely that reef-building tube worms are at least in part responsible for the formation and maintenance of beaches and barrier islands in southeast Florida (Kirtley and Tanner, 1968) (in Zale and Memfield, 1989)
    - Tube worm reefs are wave resistant and protect the shore against wave attack and retard erosion. (Zale and Memfield, 1989)

See “Coastal Green Infrastructure Research Plan for New York City,”Arcadis et al., 2014, section 3.2.3. for a detailed list of research questions related to biotic/impact questions that affect co-benefits from oyster reefs. Also see Arcadis et al., 2014 for a list of site-specific structural design questions and physical impact research questions.

CORAL REEFS

Methods of risk reduction

- Breaking of offshore waves, attenuation of wave energy. (USACE, 2013)
- Absorb low magnitude wave energy, reduce wave heights, and reduce erosion from storms and high tides. (Mazda et al., 1997; Moeller 2006, Vo-Luong and Massel, 2008 (on page 34 in Renaud et al., 2013)

Method strengths

- Reef crest and reef flat reduced 97% of wave energy consistent for small as well as hurricane sized waves. Reef crest accounted for 86% of the reduction. (Ferrario et al., 2014)
- Relatively narrow reefs can be effective for wave attenuation. (Ferrario et al., 2014)
- Function similar to that of submerged breakwaters. (NRC, 2014)

Known weaknesses

- Physical factors of reefs (depth of the reef at its shallowest point and coral composition (roughness)) have been largely unreported.
- Likely to have minimal effectiveness on storm surge.
- Areas where ocean acidification is advancing can experience decreased survival of reef systems. (Breitburg et al., 2015)

Uncertainties about utility for risk reduction & resilience

- Effectiveness can depend on tidal height (reef exposure) during storm. (GEUS, 2007 (in Renaud et al., 2013)

- Limited understanding of the role of healthy ecosystems in reducing hydrometeorological hazards when they become more frequent or extreme or when ecosystems are degraded. (Renaud et al., 2013 p. 450)

Suitable Conditions

- Most:
  - Warm water coasts -- where coral mining isn't occurring (mining reduces energy dissipation and can increases local velocity). (Renaud et al., 2013 p. 62)
  - Shallow, clear, saline water.
- Least:
  - Conditions not usually favorable for coral reef formation above and below 30^o latitude north and south.
  - Areas where ocean acidification impacts could reduce coral reef viability.

Performance factors/Performance evaluation metrics/Design metrics

- Reef width, elevation, and roughness. (USACE, 2013)
- Length of reef in the direction of wave propagation, submerged depth of flow (water depth above the reef system). (Renaud et al., 2013 p. 62)
- Geometry of the reef (porosity, tortuosity, surface roughness, and the overall void matrix). (Renaud et al., 2013 p. 62)
- Proximity to land
- Extent of reef flat (width and shallowness)

Failure/Resiliency/Post storm event recovery factors

- Slow growth rate of coral.

Capacity/Limitations of method to keep pace with climate change

- Ocean acidification and sea level rise could adversely affect long term effectiveness.
- Over long time schemes (decades to centuries), coral reefs may be able to keep pace vertically with sea level rise and/or migrate inland if not impeded by natural or fabricated barriers and if space is available. (FitzGerald et al., 2008)
  - Such adaption is limited by degree to which the ecosystem has been degraded and by its capacity to cope with other multiple stressors. (e.g., temperature rise and ocean acidification.) (Renaud et al., 2013 p. 85)

Examples of sites where implemented

- Guam. (Ferrario et al., 2014) (Ferrario et al., 2014, also provides information on costs of coral reef restoration.)
- Puerto Rico (TNC project).
- Jamaica (planned). (Renaud et al., 2013 p. 109-139)
- Tampa Bay, FL (Audubon Project using reef balls).

Most catalytic/pressing research areas

- Physical factors of reefs (depth of the reef at its shallowest point and coral composition (roughness)) have been largely unreported. (Ferrario et al., 2014; NRC, 2014) Having such information would allow models for submerged breakwaters to calculate effectiveness.
- What are the metrics to best monitor continued risk reduction effectiveness?

MANGROVES

Methods of risk reduction

- Wave attenuation and/or dissipation (USACE, 2013)
- Shoreline stabilization (USACE, 2013)
- Soil retention (USACE, 2013)
- Reduction in peak water level heights (Krauss et al., 2009)
- Debris capture
- Absorb low magnitude wave energy, reduce wave heights, and reduce erosion from storms and high tides. (Mazda et al., 1997; Moeller, 2006, Vo-Luong and Massel, 2008 (in Renaud et al., 2013 (page 34))
- Facilitate sedimentation and dampen wave stress; alleviate impact of moderate Tsunami waves (Cheong et al., 2013) (Cochard, 2008) (Algoni, 2008; Tanaka, 2009)
- Over the longer term (decades to centuries), mangroves can alter the surface elevation of the shore (influencing the bathymetry and topography), the local geometry (e.g., through progradation, which is the expansion of wetland areas towards the sea) and the location of channels (Spencer and Möller, 2012) (McIvor et al., 2012), all of which also influence the height of surges.

Method strengths

- Storm surge reduction potential has been studied in the field and with modeling (3-10in per mile), surge attenuation is nonlinear. (Zhang et al., 2012)
- Modeling indicates especially capable of attenuating short-period wind waves, reducing height by 75-100% over 1 km. (Mazda et al 2006) (in NRC, 2014)
- May reduce flooding extent and associated damage from storm surge and small to moderate Tsunamis (Spalding et al., 2014)
- Complex aerial root structure reduces wave damage while trapping manmade debris, lessening tsunami impacts to communities behind mangrove forests. (Juan Carlos Laso Bayas and Meine van Noordwijk, 2011)
- Multiple benefits beyond risk reduction. (Lacambra et al., 2013)

Known weaknesses

- Effectiveness of surge reduction a function of many internal and external factors (Arcadis et al. (2014) provides a table of factors effecting vegetation generally).
- Surge reducing potential depends on storm characteristics (most effective for fast moving storms). (NRC, 2014)
- Mangroves can only reduce storm surges when they are present over large areas. (McIvor et al., 2012)
- Wind damage during storms can reduce effectiveness.
- Takes extended periods of time for mangrove forests to become truly effective.

Uncertainties about utility for risk reduction & resilience

- Limited understanding of the role of healthy ecosystems in reducing hydrometeorological hazards when they become more frequent or extreme or when ecosystems are degraded. (Renaud et al., 2013 p. 450)
- Effectiveness still controversial (Cheong et al., 2013)

Suitable Conditions

- Most:
  - Four species in the US (each with light, temperature, salinity, pH, soil, elevation requirements) and temperature limits northern distribution (northern range appears to be expanding).
    - Primarily found in South Florida (USFWS, 2014).
- Least:
  - Considered an invasive species in Hawaiian Islands.

Performance factors/Performance evaluation metrics/Design metrics

- Vegetation width, height, density, structure, age, stiffness of plant, orientation and geometry (as related to storm direction), continuity and uniformity, health of root system, length. (Lacambra et al., 2013 p. 93)
- Forest width and relative density of exposed root systems ranked as most important for wave attenuation (both wind generated and tsunami).
  - Forest width and spacing very important for determining effectiveness.
- Water depth dictates whether wave dissipation is achieved by tree canopy or by root layer. (Gedan et al., 2011)
- Sediment composition; need sustained sediment supplies (e.g., through fluvial processes). (Cheong et al., 2013)
- Of the factors known to affect surge height: mangroves directly affect surface roughness, height of surface wind waves, and the speed of the wind directly over the water surface within areas where the vegetation reaches above the water level. (McIvor et al., 2012)
- Platform elevation.
- Predation (of seedlings/transplants of young trees).

Failure/Resiliency/Post-storm event recovery factors

- Mangroves' physical resistance and resilience to impacts of natural hazards have not been fully researched. Little is known about thresholds beyond which ecosystem changes to a different state. (Lacambra et al., 2013)
- Response times of trees to grow back can be longer than grow back times of herbaceous wetlands.

Capacity Limitations of method to keep pace with climate change

- Sedimentation rates in mangroves is "almost equal" to the rate of sea-level rise (Algoni, 2008)
- Over long time schemes (decades to centuries) may be able to keep pace vertically with sea level rise (Spalding et al., 2014) and/or migrate inland if not impeded by natural or fabricated barriers and if space is available (FitzGerald et al., 2008). However, such capabilities are limited by degree to which the ecosystem has been degraded and by its capacity to cope with other multiple stressors. (Renaud et al., 2013, p. 85)
- Changing climate can alter extent of suitable habitat (both expanding and contracting).
  - Currently, range is expanding in U.S. (Saintilan et al., 2014).

Examples of sites where implemented

- Southeast Asia (protection & restoration).
- Caribbean/Latin America (protection & restoration).

Most catalytic/pressing research needs

- What are the metrics to best monitor continued risk reduction effectiveness?

- What is the interaction of physical processes and characteristics that could enhance or attenuate wave energy? (Lacambra et al., 2013)
- What can be done to accelerate recovery and regeneration after damage?

Additional research needs

- What is the efficacy of mangroves under existing and restored conditions for reducing risk in the context of other benefits provided? (NRC, 2014)
- Opportunities to combine natural, nature-based, and structural infrastructure?
- What can be done to increase coastal resiliency in the interim period between mangrove forest implementation and the time it takes for them to become effective?

MARITIME FORESTS

Methods of risk reduction

- Wave attenuation and/or dissipation. (USACE, 2013)
- Shoreline stabilization. (USACE, 2013)
- Soil retention. (USACE, 2013)
- Reduce wind and salt spray. (Arcadis et al., 2014)
- Usually located above spring tide/behind a dune, and are able to withstand high winds, periodic flooding, salt spray, so may act as an inland barrier to surge and waves during severe storms. (Takle et al., 2007)
- Wetlands and maritime forests of a sufficient size are a natural coastal defense and may be effective in providing wave dissipation (Anderson et al., 2011), flow impedance (Wu et al., 2001), and sediment retention. Consequently, these measures can improve erosion control and mitigate shoreline retreat (Shepard et al., 2011; Wolanski, 2006)

Method strengths

- Have a "direct impact on wind conditions during storm events… Multiple studies have examined wind reduction due to windbreaks or shelterbelts used to protect agricultural fields (Berg and Limited, 2007; Takle et al., 2007; Wolanski, 2006). The zone of wind reduction extends to both windward and leeward sides of a shelterbelt." (Arcadis et al., 2014)
    - On the windward side, winds reduce for a distance of 2 to 5 times the height of the forest barrier. (Wang and Takle, 1996)
    - On the leeward side, winds reduce for a distance of 30 times the height of the forest barrier. (Wang and Takle, 1996)

Known weaknesses

- Needs to be integrated with wetland and existing ecosystems for maximum ecological and hazard mitigation benefits. Should be to be large (200 ac+) to maintain species diversity.
- Wind damage during storms can reduce effectiveness.
- Takes extended periods of time for maritime forests to become truly effective.

Uncertainties about utility for risk reduction & resilience

- Limited understanding of the role of healthy ecosystems in reducing hydrometeorological hazards when they become more frequent or extreme or when ecosystems are degraded. (Renaud et al., 2013)

Suitable Conditions

- Most:
    - Barrier islands, estuarine shorelines, coastal sand ridges. (Bellis, 1995)
    - Maritime forests adapted to high wind velocities, sandy soils, salt spray. (Bellis, 1995)

Performance Factors/Performance Evaluation Metrics/Design Metrics

- Vegetation height and density. (USACE, 2013)
- Forest dimension. (USACE, 2013)
- Sediment composition. (USACE, 2013)
- Platform elevation. (USACE, 2013)
- A tree's ability to withstand hurricane winds was dependent on the strength of the wind, the size and shape of the crown, the extent and depth of the root system, the antecedent soil moisture content, and the shape of the bole. (Touliatos and Roth, 1971, in Bellis, 1995)

Failure/ Resiliency/Post-storm event recovery factors

- With sufficient sediment load and nutrient load, maritime forests can self-recover from moderate damage due to storm events. (Arcadis et al., 2014)
- Hurricanes can uproot poorly anchored trees and strip well-anchored trees of their leaves. Secondary effects included salt-aerosol damage to foliage and flooding of root systems by brackish water. (Bellis, 1995)
- Response times of trees to grow back can be longer than grow back time herbaceous wetlands.

Capacity/Limitations of method to keep pace with climate change

- Maritime forests are less sensitive to sea-level rise than marshes and may collapse in subsequent marsh submergence. (Arcadis et al., 2014)
- With sufficient sediment load and nutrient load, maritime forests can self-adapt to gradual hazards, such as sea-level rise, and can self-recover from moderate damage due to storm events or ice cover. (Arcadis et al., 2014)

Examples of sites where implemented

- No intentionally installed maritime forests identified

Most catalytic/pressing research needs

- What are the bio-mechanical properties of coastal wetlands and coastal and maritime forests? (Arcadis et al., 2014)
- What can be done to increase coastal resiliency in the interim period between maritime forest implementation and the time it takes for them to become effective?
- Field measurements to verify the impacts of maritime forests because trees vary in size and are arranged randomly and more coarsely than in shelter belts. (Arcadis et al., 2014)

Additional research needs

- What can be done to accelerate recovery and regeneration after damage?
- Opportunities to combine natural, nature-based, and structural infrastructure?

COASTAL WETLANDS (Non-Mangrove)

Methods of risk reduction

- Breaking of offshore waves, attenuation of wave energy, and increased infiltration. (USACE, 2013)
- Shoreline stabilization (accretion, erosion reduction and/or positive elevation changes). (NRC, 2014)
- Potentially, tidal flooding and storm tide inundation can be influenced because of the dense vegetation over restored marshland. These energy and momentum dissipations are caused by resistance to the flow due to shallow bathymetry, rough bottom friction, and vegetal drag force.
- Decrease shoreline erosion, as the expansive root system produced by marsh grasses increases soil integrity and resistance to wave-driven erosion. Marshes dampen waves, suppress erosion rates, and thereby reduce wave impact on adjacent levees. (Cheong et al., 2013) (Kirwan et al., 2010; Silliman et al., 2012)

Method strengths

- Vegetation is responsible for up to 60% of the wave attenuation during storms events. 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) Even small, narrow wetlands provide wave attenuation. (Gedan et al., 2011)
- Sea Level Affecting Marshes Model (SLAMM), Marsh Equilibrium Model (MEM), Wetlands Morphology Model of the Louisiana State Coastal Master Plan, and other ecology models exist for simulation of wetland evolution.

Known weaknesses

- Quantitative effects not fully understood. (NRC, 2014)
- No direct studies stating the prioritization of factors in hazard mitigation and wetland resiliency. (Arcadis et al., 2014)
- No data on capacity of saltmarshes to reduce the extent of flooding. (Shepard et al., 2011)
- Requires space, sediment (fill to create) and erosion protection until vegetation establishes in higher energy areas.
- Limited understanding of the effects of vegetation breakage and uprooting on both circulation and wave models, which may lead to overestimation of vegetation effects.
- Water logged wetlands may not provide same wave attenuation benefits, might increase wave energy. (Resio and Westerink, 2008)
- The potential of wetlands to reduce storm surge has typically been expressed as a constant attenuation rate, but the relationship is much more complex. Results suggest that wetlands do have the potential to reduce surges but the magnitude of attenuation is dependent on the surrounding coastal landscape and the strength and duration of the storm forcing. (Wamsley et al., 2010)
- Maximum wave attenuation may be limited by a wetland's attenuation potential. (Möller, 2006)
- Gap in knowledge in scale studies. Investment necessary in field level investigation.

Uncertainties about utility for risk reduction & resilience

- Limited understanding of the role of healthy ecosystems in reducing hydrometerological hazards when they become more frequent or extreme or when ecosystems are degraded. (Renaud et al., 2013 p. 450)
- The degree to which wetlands attenuate surge is the subject of debate and difficult to assess. Models can estimate surges over wetlands, although the formulations are missing key processes and model advancements are necessary. (Wamsley et al., 2010)
    - Manning's coefficients for a given type of vegetation can vary with time (e.g., seasonal), submergence degree, and flow velocity (related to vegetative stiffness). The variation may be profound during a storm event as vegetation flexes and breaks. (Arcadis et al., 2014)
    - In many numerical models, the vegetal drag exerted on both oscillatory and steady flow is often lumped in with the resistance due to bottom friction. For instance, a Manning's coefficient is used to estimate the flow resistance due to various vegetation types. (e.g., Bunya et al. 2010). (in Arcadis et al., 2014)
    - Three-way interaction is often missing in models used to evaluate risk and scour reduction of a vegetated system such as wetlands and maritime forests. The three-way interaction of waves, currents, and vegetation should be thoroughly considered in a coupled model system, yet this coupling is not present in most modeling efforts; the scientific communities' understanding is currently inadequate to provide guidance beyond basic principles. Numerical modeling based studies to date are often completed considering a two-way interaction between vegetation and either wind waves or longer period waves, such as surge or tides. In a real-world storm scenario, the interaction between currents, wind waves, and vegetation can be very complicated, especially during a storm event. (Arcadis et al., 2014)

Suitable Conditions

- Most:
    - Coastal plain, sandy/silty shorelines with historic or degraded wetlands.
- Least:
    - Rocky shorelines, rock outcrops; high energy shorelines.

Performance factors/Performance evaluation metrics/Design metrics

- Marsh, wetland, or SAV elevation and continuity. (USACE, 2013)
- Vegetation type and density. (USACE, 2013)
- For wave attenuation: marsh width, vegetation height, stem stiffness, and density. (Bouma et al., 2005; Sheng et al., 2012; Shepard et al., 2011) (from Arcadis et al., 2014)
- Storm characteristics play important role in attenuation of storm surge by vegetation -- faster storms more effectively attenuated than slow. (Shepard et al., 2011)
- Greater attenuation for wind waves during low energy events than for storm surge events. (Gedan et al., 2011)
- The effectiveness of vegetation resistance is dependent on internal factors such as density, height, and width of the vegetation canopy, as well as external factors such as the intensity and forward speed of a hurricane.
- Among internal factors, emergent, stiffer, denser, and higher vegetation can dissipate wave energy, reduce inland storm surge height and extent, and limit tidal flooding more effectively than submerged, flexible, and short-stemmed vegetation (Nepf and Vivoni 2000; Nikora et al. 2001; Irish et al. 2008; Chen and Zhao 2012; Barbier 2013). (in Arcadis et al., 2014)

- Water depth is a critically important external factor because vegetation resistance is most influential when the vegetation roughness layer takes up a sufficient portion of the total water depth. (Nepf and Vivoni 2000; Wilson and Horritt 2002) (in Arcadis et al., 2014)
- Inherently, drag coefficients, wave frequency, and flow structure are affected by the three-way interaction in comparison to wave-vegetation, current-vegetation, or wave-current two-way interactions (Li and Yan 2007; Patil and Singh 2009). (in Arcadis et al., 2014)
- An often-applied metric for evaluating the hazard mitigation potential of vegetation is hydrodynamic quantity (e.g., wave height, water level) reduction or a dissipation rate over a given distance. This is done by comparing wave heights or water levels inland of wetlands and forests to incident conditions at the seaward edge. (e.g., USACE 1963; Fitzpatrick et al. 2009). (in Arcadis et al., 2014)
- Hazard mitigation can also be assessed using aggregated parameters, such as a percent reduction of total inundation volume over a given area.
- At locations susceptible to erosion and scour, a horizontal retreat rate, as well as changes in vertical profile, can be used to evaluate mitigation of gradual hazards.

Failure/Resiliency/Post-storm event recovery factors

- Wetland losses caused by hurricane impacts depend directly on impact duration, which is controlled by the diameter of hurricane-force winds, forward speed of the storm, and wetland distance over which the storm passes. (Morton and Barras, 2011)
- Category 1 Hurricane Irene damaged 76% of bulkheads, had no impact on surface elevation of mashes and temporary reductions in marsh vegetation density recovered to pre-storm levels within one year, suggesting that saltmarshes protected against smaller hurricanes and larger storm events. (Gittman et al., 2014)

Capacity/Limitations of method to keep pace with climate change

- Under certain circumstances, salt marshes may be able to maintain the coastline relative to sea level rise by accreting sediment at a level comparable to or even higher than sea level rise providing a further reduction in vulnerability to hazards and climate change. (Cahoon et al., 2006; Hale et al., 2009)
- With sufficient sediment load and nutrient load, constructed wetlands can self-adapt to gradual hazards, such as sea-level rise, and can self-recover from moderate damage due to storm events or ice cover. (Arcadis et al., 2014)
- For backbarrier marshes adjacent to restored barrier islands with sufficient height to restrict most overwash events (> 3 – 4 meters), sediment sources will be reduced and in some cases marshes may not keep pace with relative sea level rise. (Campbell et al., 2005)

Examples of sites where implemented

- New Orleans, West Lake Pontchartrain.
- Skagit Bay Diking District – planning.
- Gilman and Ellison (2007) provide estimates for mangrove restoration.

Most catalytic/pressing research needs

- Numerical models that simulate the relevant physical processes can provide valuable information on how to best integrate wetlands into coastal protection plans.
  - Numerical models could be improved to more accurately predict the reduction in storm surge, wind waves, and scour related to vegetative resistance.

    - Modeling of the three-way interaction of waves, currents, and vegetation should be thoroughly considered in a coupled model system.
    - Improve numerical models and the overall state of the science related to vegetal drag based on field observations and physical modeling experiments to improve the understanding of the bio-mechanical properties of coastal wetlands.
        - Figure out how patch dynamics affect the wave or surge reduction potential – how patch dynamics (fragmentation, patch arrangement) can be parameterized.
            - Quantifying the benefits of continuous wetlands as opposed to channeled wetlands; wetland/water ratio.
        - In order to implement a better parameterization of vegetative roughness in numerical models, it is important to understand vegetal drag and Manning's coefficients under both typical and stormy conditions for prevalent species. (Arcadis et al., 2014)
            - What are the appropriate formulas to estimate vegetative resistance for a wide range of submergence degrees (from emergent to deeply submerged)?
            - What are the bio-mechanical properties of specific plants (e.g., *Phragmites* vs. *Spartina*) – which are more effective for risk reduction? How can a physical model be set up to help improve the understanding of friction coefficients?
            - How sensitive are storm tide, wave, and erosion predictions to flow-condition dependent Manning's coefficients?
    - Effectively incorporate fine grained sediment into our modeling.
    - Model resolution – how fine must a wetland model be in order to better understand how wetland feature components interact with one another?
- Bridge the gap between small-scale laboratory findings and real-world storm scenarios.
- Figure out the metrics to best monitor continued risk reduction effectiveness.

Additional research needs

- An accurate method to quantify the effect of wetlands on coastal surge levels is required. (Wamsley et al., 2010) Understanding the scale (horizontal and vertical) where wetlands are effective at reducing surge to determine the necessary wetland footprint for providing targeted levels of protection or for assessing contribution to protection.
- How to optimally create wetlands to provide max benefits at minimum cost (Renaud et al., 2013 p. 451)
- Determine what the 'threshold of stability' is to know when wetland systems will fail.
- Determine the performance of wetlands' ability to dissipate waves under high frequency versus low frequency events.
- Improve understanding of ice volume and coverage, as well as the expected vegetation uprooting forces accompanying it.
    - Quantify the static and dynamic ice forces being exerted on natural shorelines.
    - Determine which plant communities are most vulnerable to uprooting related to ice.

See "Coastal Green Infrastructure Research Plan for New York City," Arcadis et al., 2014, section 3.1.3. for a detailed list of research questions related to the resiliency of wetlands.

Conclusions

EDF's literature review and consultation with experts confirms that there is sufficient confidence in the ability of natural infrastructure and nature-based measures to reduce impacts of coastal storms and sea level rise to coastal communities such that these approaches should be routinely considered as viable options by decision-makers.

With what we know now, implementation of these approaches can be facilitated by developing detailed engineering guidelines that provide functional and structural design guidance as well as address other design issues. Such guidance will facilitate quantification of performance. Federal policies and practices require quantification of the risk reduction benefits if federal funds for flood risk reduction actions are proposed to be used for restoring or creating natural infrastructure and nature based measures. Quantification of risk reduction benefits is also a necessary precursor to developing new market-based or private sector funding options for communities seeking financial support for measures that will enhance their resilience to coastal storms and sea level rise.

The value of natural infrastructure and nature-based methods does not rest solely in risk reduction as these solutions offer other valuable ecosystem services – co-benefits which are generally absent from traditional hardened infrastructure. Incorporation of ecosystem services into cost-benefit and environmental impact analyses will advance more informed decision-making on the part of communities about how they wish to approach increasing their resiliency. As ecosystem service evaluation methodologies become more broadly accepted and integrated into investment decision-making, natural infrastructure solutions should be more highly valued for their economic, environmental, and risk reduction contributions.

This EDF report focused on the potential storm damage reduction benefits of natural infrastructure and nature-based measures. We have not examined in detail the degree to which nature-based coastal protection projects, like living shorelines and constructed beaches, function as habitat or true ecosystem restoration. Nor did we look at the environmental impacts of restoring or creating anew natural infrastructure or nature-based measures. All of these factors are important in deciding what set of measures to employ.

As projects using natural infrastructure and nature-based methods are implemented, appropriate monitoring and information sharing should be incorporated. We need to: expand knowledge of the circumstances where these measures work best; document whether they performed as expected; learn how traditional structural, nonstructural and natural infrastructure and nature based measures can optimally work together; understand how coastal processes are effected; and, track the measures' life expectancy in a climate changing world.

One thing is clear, rising sea levels threathen ecological systems and human communities. Restoring the buffering capacity of natural infrastructure is a "no regrets" approach to coastal resiliency that addresses the needs of human communities and ecological systems. If one of our goals is to preserve existing natural coastal ecosystems over the next century and beyond, we must realize that this goal can only be met by allowing some shorelines to move. The best hope for coastal ecosystems will be finding an economically sound approach to letting some areas regain their natural, dynamic nature. We should pursue nature-based coastal protection as a supremely better alternative than large-scale hardening of our shores, and we must recognize that it will not be possible to hold every shoreline in place forever. Combinations of nonstructural, natural infrastructure and nature-based, and structural measures will be necessary and must fully recognize and work within the context of dynamic coastal processes and shifting points equilibrium caused by increasingly intense storms and faster paced sea-level rise.

Table 1: Natural Infrastructure and Nature-based Measures: Summary of risk reduction performance and engineering guidance, costs, and factors relevant to climate change.

Key **-** = Low confidence, feature not likely to address **+** = High confidence, data available **~** = Limited confidence refinement needed Blank = need data			Risk Reduction Performance[1]					Design/O&M Criteria	Costs[2] per linear foot		Other Factors	
			Reduce coastal erosion/ Shoreline Stabilization	Nuisance floods (high tides with sea level rise)	Short wave (<2') attenu-ation (Stabilize Sediment)	Reduce force & height of med. waves (2- 5')	Storm Surge (low frequency extreme events)	(for performance areas specific to feature)	Construction	Annual O&M[3]	Mitigates climate change (CO_2 sequest-ration)	Adaptability to sea level rise & changing community needs
Strategy	Structural	Groins	+[4]	-	+			+	$2-5k	$.1-.5k	No	
		Breakwaters	+[4]	-	+	+		+	$5 - 10k	>$.5k	No	Variable
		Seawall/ Revetments/ Bulkheads	+[4]	+		+	+	+	$5-10k $5-10k $2-5k	>$.5k $.1 -.5k $.1 -.5k	No	
		Surge Barriers	-			+	+	+	>$10k[5]		No	
	Existing Natural	Wetlands	+		+	~	~	N/A	N/A		Yes	Yes
		Mangroves/ coastal forest	+		+	+	+	N/A	N/A		Yes	Yes
		Vegetated Dunes	+		+	+	+	N/A	N/A		~	Yes
	Nature-based	Beach Nourishment	+	+	+	+		+	$2k - 5k[6]	$.1k -.5k		Yes
		Vegetated Dune creation	+	+	+	+	+	+	$.03k - 5k[6]	$.1k -.5k	~	Yes
		Barrier Island Restoration	+	+	+	+	+	+	$0.76k - $1.1k[7]			Yes
		Small scale edging and sills (living shorelines)	+	~	+				$1k-2k	<$.1k	Variable	Yes
		Restored Oyster/Shell-fish Reefs	+		+	~	~	Possible, akin to low breakwaters	$.23k - .24k[8]		Yes	Yes
		Restored/ Created Coral Reefs	+		+	~	~	Possible, akin to low breakwaters	$.2k – 508k[9]		~	
		Restored Maritime Forests (including Mangroves)	+	+	+	+	+		$.23k - 216k[10] /ha (mangroves)		Yes	Yes
		Restored Wetlands[11]	+	+	+	~		-	$0.81k- 36.4k/ha[12]		Yes	Yes

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[1] General coastal risk reduction performance factors include storm intensity, track, forward speed, surrounding local bathymetry and topography

[2] USACE and NOAA (2015) is the source for most costs in this table unless otherwise noted with a footnote. Values not adjusted for inflation.

[3] Based on 50 year project life

[4] While these hardened coastal features can effectively reduce erosion in certain coastal areas, they also often lead to increased or unwanted erosion in other coastal areas.

[5] No data for surge barriers presented by linear foot, but due to size, engineering complexity and more difficult construction conditions, estimated to be greater than $10k/linear foot.

[6] Higher cost is for beach nourishment with vegetated dune creation. Low end estimate based on a NRDA Trustees (2012) for Pensacola Beach.

[7] Day et al. (2005)

[8] Gregalis et al. (2008)

[9] Ferrario et al. (2014)

[10] Gilman and Ellison (2007)

[11] Various methods including sediment diversions or hydrological reconnection

[12] Coastal Resources Management Council's "The Costs of Environmental Restoration Projects"

Table 2: List of Participants and External Reviewers

The following scientists, engineers, program managers, and financers were present at the May 29, 2015 workshop:

Name	Organization
Mr. Dick Wright	American Society of Civil Engineers
Dr. Denise Reed	The Water Institute of the Gulf
Dr. David L. Kriebel	US Navy Academy
Dr. Tony Dalrymple	Johns Hopkins University
Dr. Jennifer Irish	Virginia Tech University
Dr. Todd Bridges	USACE, Environmental R&D Center
Dr. Robert Young	Western Carolina University
Dr. Karl Nordstrom	Rutgers University
Mr. Hugh Roberts	Arcadis
Mr. John Headland	Headland and Associates
Mr. Steve Goldbeck	San Francisco Bay Conservation & Development Commission
Dr. Michael Oppenheimer	Princeton University, Climate Change
Ms. Roselle Henn	USACE, Storm Reduction Center of Excellence
Ms. Lindene Patton	Corelogic
Mr. Jonathan Wescott	Federal Emergency Management Agency
Mr. Robert Hyman	Department of Transportation
Mr. Nicholas Benjamin Claude Desramaut	World Bank, Disaster Risk Management Specialist
Mr. Nick Shufro	PricewaterhouseCoopers, R!SE
Mr. Joe Bouchard	blue moon fund, Coastal Resilience Fellow

The following scientists and engineers contributed to the external review process of the literature review, summary table, and workshop summary report:

Name	Organization
Dr. Kate White	USACE Lead for Climate Preparedness and Resilience
Dr. Bret Webb	University of Southern Alabama
Dr. Paul Kirshen	University of New Hampshire

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