Ecosystem-Service Assessment: Research Needs for Coastal Green Infrastructure

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Ecosystem-Service Assessment: Research Needs for Coastal Green Infrastructure

PRODUCT OF THE

Committee on Environment, Natural Resources, and Sustainability

OF THE

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

August 2015

EXECUTIVE OFFICE OF THE PRESIDENT
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL
WASHINGTON, D.C. 20502

Dear Colleagues:

We are pleased to transmit the report "Ecosystem-Service Assessment: Research Needs for Coastal Green Infrastructure." This report, prepared by the Coastal Green Infrastructure and Ecosystem Services (CGIES) Task Force of the National Science and Technology Council (NSTC), Committee on Environment, Natural Resources, and Sustainability (CENRS), Subcommittee on Ecological Systems (SES), recommends areas for prioritized Federal research to support the integration of coastal green infrastructure into risk reduction, resilience planning, and decision making. The report also serves as a useful reference for planners and decision makers by providing an introduction to major categories of coastal green infrastructure and associated ecosystem services, as well as factors that should be taken into account when considering if, when, and how to incorporate coastal green infrastructure into a given setting.

This document was developed in response to Recommendation 22 of the *Hurricane Sandy Rebuilding Strategy*, which was designed to help institutionalize the best practices learned during the Hurricane Sandy rebuilding effort for integrating green infrastructure into coastal resilience strategies, and to provide transferable methods for advancing these approaches beyond the Sandy-affected region. The report also aligns with recommendations in the President's Council of Advisors on Science and Technology's report to the President on *Sustaining Environmental Capital: Protecting Society and the Economy*, and complements a number of Federal efforts to advance the use of green infrastructure and ecosystem-service approaches.

Sincerely,

Thomas Burke, EPA (Co-Chair, CENRS) — 8/25/15 Date

Tamara Dickinson, OSTP (Co-Chair, CENRS) — 8/25/15 Date

Kathryn Sullivan, NOAA (Co-Chair, CENRS) — 8/25/15 Date

About the National Science and Technology Council

The National Science and Technology Council (NSTC) is the principal means by which the Executive Branch coordinates science and technology policy across the diverse entities that make up the Federal research and development (R&D) enterprise. One of the NSTC's primary objectives is establishing clear national goals for Federal science and technology investments. The NSTC prepares R&D packages aimed at accomplishing multiple national goals. The NSTC's work is organized under five committees: Environment, Natural Resources, and Sustainability; Homeland and National Security; Science, Technology, Engineering, and Mathematics (STEM) Education; Science; and Technology. Each of these committees oversees subcommittees and working groups that are focused on different aspects of science and technology. More information is available at www.whitehouse.gov/ostp/nstc.

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The Office of Science and Technology Policy (OSTP) was established by the National Science and Technology Policy, Organization, and Priorities Act of 1976. OSTP's responsibilities include advising the President in policy formulation and budget development on questions in which science and technology are important elements; articulating the President's science and technology policy and programs; and fostering strong partnerships among Federal, state, and local governments, and the scientific communities in industry and academia. The Director of OSTP also serves as Assistant to the President for Science and Technology and manages the NSTC. More information is available at www.whitehouse.gov/ostp.

About the Coastal Green Infrastructure and Ecosystem Services (CGIES) Task Force

Hurricane Sandy struck the Eastern seaboard of the United States in October 2012. Shortly thereafter, Executive Order 13632 established the Hurricane Sandy Rebuilding Task Force (HSRTF), comprised of senior Administration officials from 24 Federal executive departments, agencies, and offices, to oversee Federal involvement in the rebuilding effort. In August 2013, the HSRTF released the *Hurricane Sandy Rebuilding Strategy* (Strategy),[1] which laid out a set of recommendations to guide Sandy recovery, while simultaneously enhancing community and national preparedness for future disasters. Recommendations 19 – 22 of the Strategy advise advancing the integration of green infrastructure into coastal resilience strategies, with a focus on investments and projects funded by the Disaster Relief Appropriations Act of 2013 (commonly referred to as the "Sandy Supplemental"). Recommendations 19 – 21 were completed by early July 2014.[2]

Recommendation 22 was designed to help institutionalize the best practices learned during the implementation of recommendations 19 – 21 and to provide transferable methods for advancing these approaches beyond the Sandy-affected region. In response to this recommendation, the White House Office of Science and Technology Policy (OSTP) convened the Coastal Green Infrastructure and Ecosystem Services (CGIES) Task Force, an interagency group organized under the National Science and Technology Council (NSTC), Committee on Environment, Natural Resources, and Sustainability (CENRS), Subcommittee on Ecological Systems (SES). The Task Force is co-chaired by the Department of the Interior/U.S. Geological Survey and the Department of Commerce/National Oceanic and Atmospheric Administration.

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[1] http://portal.hud.gov/hudportal/documents/huddoc?id=hsrebuildingstrategy.pdf.

[2] More information on the implementation of these recommendations is available at http://portal.hud.gov/hudportal/HUD?src=/sandyrebuilding/recoveryprogress.

The CGIES Task Force was responsible for advancing the research and development component of Recommendation 22 by: (1) identifying knowledge gaps that impede the recognition, quantification, and valuation of benefits provided by green infrastructure in coastal areas, with a focus on benefits that enhance coastal resilience to climate change; (2) identifying knowledge gaps that impede the integration of green infrastructure into coastal climate-resilience planning and response; and (3) developing a Federal research and development agenda that outlines specific needs and opportunities for addressing these knowledge gaps. This report, *Ecosystem-Service Assessment: Research Needs for Coastal Green Infrastructure* is the product of the CGIES Task Force's efforts.

About this Document

This document was developed by the Coastal Green Infrastructure and Ecosystem Services Task Force. The document was published by OSTP.

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SUBCOMMITTEE ON ECOLOGICAL SYSTEMS
COASTAL GREEN INFRASTRUCTURE AND ECOSYSTEM SERVICES TASK FORCE

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Executive Summary

In 2012, Hurricane Sandy struck the Eastern seaboard of the United States. Recovery efforts highlighted the opportunity to increase use of green infrastructure[3] in coastal areas, both to protect the coastline against future storms and climate-related impacts and to enhance the resilience of coastal communities.

Substantial knowledge and application gaps currently impede more widespread adoption of coastal green infrastructure (CGI) strategies. CGI has been demonstrably effective at enhancing resilience under certain circumstances, and the potential and effectiveness of green infrastructure varies across regions, scenarios, and decision contexts. Optimal use of CGI requires a thorough understanding of a community's needs and the ecosystem services[4] (including co-benefits) that are likely to be provided by alternative infrastructure approaches under different conditions. Greater consistency is also needed in the structure and application of methods used to identify, quantify, and value these services.

Ecosystem-Service Assessment: Research Needs for Coastal Green Infrastructure addresses these gaps and responds to recommendations in the Federal Hurricane Sandy Rebuilding Task Force's *Hurricane Sandy Rebuilding Strategy* by:

- providing key information needed by Federal planners and decision makers to advance the broad integration of CGI; and
- identifying priority research topics related to the use of CGI to reduce vulnerability and enhance resilience to climate-related threats in coastal areas.

The report builds on, and is aligned with, recent and ongoing efforts to advance the integration of ecosystem services into Federal decision making. Fundamental research is necessary to understand both natural and human components of vulnerability and resilience in coastal areas. Although this report focuses on science-based information and research needs for CGI, many of the concepts and research recommendations articulated herein are applicable to ecosystem-service assessment in a broad range of settings. Progress in these areas has the potential to benefit Federal agencies, resource managers, communities, and other stakeholders in coastal and non-coastal areas alike.

Several types of CGI provide ecosystem services – including wave and wind attenuation, soil stabilization and sediment capture, and water flow and flood regulation – that can help reduce vulnerability and enhance resilience to coastal climate-related threats. These types of CGI primarily include, but are not limited to, salt marshes, mangroves, reefs, seagrass beds, and sand beaches and dunes, as well as hybrid approaches that strategically combine one or more of these features with non-natural structures. CGI (including hybrid approaches) also delivers co-benefits that can be leveraged to simultaneously achieve additional social, economic, and environmental objectives in ways that gray infrastructure does not. Those seeking to integrate CGI into planning and decision making should understand how the ecosystem services and co-benefits associated with such approaches can vary under different conditions, across and within distinct geographic regions, and through time.

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[3] In this document, usage of the term "green infrastructure" is consistent with the definition provided in the *Hurricane Sandy Rebuilding Strategy*: "The integration of natural systems and processes, or engineered systems that mimic natural systems and processes, into investments in resilient infrastructure." It is important to recognize, however, that terminology for this concept is not consistent across the Federal landscape. For instance, the Environmental Protection Agency defines green infrastructure more narrowly as a water-management approach, while the U.S. Army Corps of Engineers has recently begun using the term "natural and nature-based features (NNBF)" to refer to the broader concept of green infrastructure as defined in the *Strategy.* For further discussion, see Bridges et al. (2015).

[4] The direct or indirect contribution, including economic, environmental, and social effects, which ecosystems make to the environment and human populations (White House Council on Environmental Quality, 2013).

Recognition and understanding of the services provided by CGI are necessary, but not sufficient, prerequisites for the broad integration of CGI (including hybrid approaches) into coastal resilience and risk-reduction strategies. To justify the use of CGI, planners and decision makers also need information demonstrating that marginal changes in the provision of associated ecosystem services (including co-benefits) are worth the necessary investments and tradeoffs. Such justification generally requires ecosystem-service assessment, i.e., an integrated and systematic approach to characterizing all significant ecosystem services in an area of interest. Such assessment is generally understood to include one or more of three broad components: qualitative identification and description of significant ecosystem services associated with the entity under consideration; quantitative examination of marginal changes in service provision; and valuation (monetary or non-monetary) of these changes.

There are important outstanding questions about optimal methodologies for identification, description, examination, and valuation of ecosystem services, as well as concerns that heavy reliance on such methodologies may have unintended or unforeseen consequences. Yet there are also several compelling reasons to integrate ecosystem-service considerations into planning and decision making, including:

- Avoiding unforeseen over-exploitation and degradation of natural resources.
- Ensuring that Federally-required economic analyses include the full range of benefits provided by natural systems.
- Supporting efficient allocation of resources.
- Drawing attention to the critical contributions that natural systems make to the productivity, resilience, and livability of human communities.

Additional research into best practices for ecosystem-service valuation – particularly with regard to (1) widely-accepted valuation methodologies that do not rely on market transactions and (2) the valid use of benefit transfer[5] to reduce the intense resource and logistical requirements of accurately and fully accounting for the benefits and tradeoffs associated with ecosystem services – will support broader integration of ecosystem-service considerations into planning and decision making, with corresponding realization of the advantages outlined above. Results of ecosystem-service assessments should be delivered in a way that facilitates integration into broader planning and decision-making contexts, along with key factors, including management objectives, site characteristics and scale, socioeconomic considerations, policy directives, time-dependent considerations, tradeoffs, and financing.

Based on the information presented and knowledge gaps identified in this report, the CGIES Task Force recommends that Federal departments and agencies coordinate and collaborate on priority research needs under five topics (Table 1).[6]

Table 1. Priority areas for collaborative Federal research

Topic 1: Metrics	
Driving question	Priority research needs
How can significant changes in relevant inputs, outputs, and outcomes associated with CGI be measured?	(a) Review and synthesize existing metrics. (b) Recommend metrics for major types of coastal infrastructure approaches. (c) Develop new metrics, as needed.

[5] The process of applying the monetary values estimated in existing empirical studies to assess the value of a quantified effect in a different study (EPA, 1999).

[6] See Section 5 for the full text of the recommendations, which includes details on topics and specific areas of focus.

Topic 2: Ecological production functions[7]	
Driving question	Priority research needs
How can capacities be improved for estimating the effects of changes in the structure, function, and dynamics of ecosystems connected to CGI on outputs that are directly relevant and useful to decision makers?	(a) Assess performance of CGI under design and extreme conditions. (b) Examine effects of combining green and gray infrastructure into hybrid approaches. (c) Understand and assess the interdependencies between and among coastal infrastructure, sea-level rise, water flows, coastal erosion, winds, and sediment movement. (d) Characterize non-linearities in ecological production functions. (e) Characterize co-benefits associated with coastal infrastructure approaches. (f) Characterize uncertainty and risk associated with ecological production functions.
Topic 3: Ecosystem-service valuation approaches	
Driving question	Priority research needs
What is needed to facilitate monetary and non-monetary valuation of ecosystem services associated with CGI?	(a) Improve methodologies for non-market valuation. (b) Improve methodologies for benefit transfer.
Topic 4: Socioeconomic and behavioral factors	
Driving question	Priority research needs
How do key socioeconomic and behavioral factors affect delivery of ecosystem services provided by CGI? How do linkages among biophysical, socioeconomic, and behavioral dynamics affect broader ecological, economic, and social outcomes?	(a) Identify key socioeconomic and behavioral drivers. (b) Characterize causes and effects of changes in drivers. (c) Model outcomes to help understand and predict linkages among drivers.
Topic 5: Decision support	
Driving question	Priority research needs
What strategies can be used to provide stakeholders with the information and tools they need in order to include ecosystem-service considerations in decision-making processes?	(a) Identify appropriate CGI performance and cost objectives. (b) Develop frameworks for demonstrating and validating objectives. (c) Create tools to inform CGI site selection. (d) Create tools to help reconcile multiple planning and decision-making considerations. (e) Identify and promote best practices for management of CGI data. Facilitate sharing of information resources.

[7] Mathematical expressions that estimate the effects of changes in the structure, function, and dynamics of an ecosystem on outputs that are directly relevant and useful to decision makers (U.S. Army Corps of Engineers, 2015).

1. Introduction

1.1 Purpose

In 2012, Hurricane Sandy struck the Eastern seaboard of the United States. The storm was associated with 72 direct deaths and caused damages exceeding $50 billion (NOAA, 2013), drawing attention to the vulnerability of U.S. coasts and the criticality of investing in coastal risk reduction and resilience, particularly to both the episodic and chronic effects of climate change. The *Hurricane Sandy Rebuilding Strategy* (HSRTF, 2013) laid out a set of recommendations to guide Sandy recovery, while simultaneously enhancing community and national preparedness for future disasters. The report highlighted the opportunity to increase use of green infrastructure[8] in coastal areas, both to protect the coastline against future storms and climate-related impacts and to enhance the resilience of coastal communities. Recommendation 22 of the *Strategy* specifically calls on Federal agencies to:

> "Develop a consistent approach to valuing the benefits of green approaches to infrastructure development and develop tools, data, and best practices to advance the broad integration of green infrastructure."

Ecosystem-Service Assessment: Research Needs for Coastal Green Infrastructure responds to Recommendation 22 by:

- providing key information needed by Federal planners and decision makers to advance the broad integration of coastal green infrastructure (CGI); and
- identifying priority research topics related to the use of CGI to reduce vulnerability and enhance resilience to climate-related threats in coastal areas.

The report includes particular attention to the relationship between green infrastructure and "ecosystem services." Ecosystem services are the direct or indirect contributions, including economic, environmental, and social effects, which ecosystems make to the environment and human populations (White House Council on Environmental Quality, 2013),[9] including tangible goods and benefits (such as the provision of food and materials), regulating and protective services (such as carbon sequestration or flood control), recreational opportunities, and cultural and aesthetic benefits.[10] Many of these contributions are not traded and priced in marketplaces, making them difficult to include in benefit-cost analyses and other decision-making processes unless they are specifically recognized, quantified, and valued.[11]The report builds on, and is aligned with, recent and ongoing efforts to advance the integration

[8] In this document, usage of the term "green infrastructure" is consistent with the definition provided in the *Hurricane Sandy Rebuilding Strategy*: "The integration of natural systems and processes, or engineered systems that mimic natural systems and processes, into investments in resilient infrastructure." It is important to recognize, however, that terminology for this concept is not consistent across the Federal landscape. For instance, the Environmental Protection Agency defines green infrastructure more narrowly as a water management approach, while the U.S. Army Corps of Engineers has recently begun using the term "natural and nature-based features (NNBF)" to refer to the broader concept of green infrastructure as defined in the *Strategy*. For further discussion, see Bridges et al. (2015).

[9] Further discussion of the concept and additional definitions of ecosystem services can be found in the Millennium Ecosystem Assessment, Boyd and Banzhaf (2007), EPA (2009), and Fisher et al. (2009).

[10] The *Hurricane Sandy Rebuilding Strategy* specifically calls out the following ecosystem service examples for consideration, integration, and, where feasible and appropriate, valuation as part of Federal infrastructure investment: "(1) provision of habitat (coastal, inter-coastal, inland); (2) landscape conservation for the tourism, recreation, and aesthetic values on which economies depend; (3) watershed protection for clean drinking water and improved flood management; (4) threatened and endangered species conservation and restoration; and (5) other associated ecosystem services from which people derive benefits (e.g., aquaculture and recreational and commercial fishing)."

[11] More information on these topics is contained in Section 3.

of ecosystem services into Federal decision making. Such efforts include, among others, work being carried out in response to:

- The 2011 Report to the President *Sustaining Environmental Capital: Protecting Society and the Economy*,[12] prepared by the President's Council of Advisors on Science and Technology (PCAST);
- The 2014 *Priority Agenda: Enhancing the Climate Resilience of America's Natural Resources*,[13] prepared by Climate and Natural Resources Working Group (CNRWG) of the Administration's interagency Council on Climate Preparedness and Resilience; and
- Executive Order (E.O.) 13690: "Establishing a Federal Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input,"[14] which establishes "a flexible framework to increase resilience against flooding and help preserve the natural values of floodplains."

Although the report focuses on science-based information and research needs for CGI, many of the concepts and research recommendations articulated herein are applicable to ecosystem-service assessment in a broad range of settings. Progress in these areas has the potential to benefit Federal agencies, resource managers, communities, and other stakeholders in coastal and non-coastal areas alike.

1.2 Focus on coastal green infrastructure

Coastal areas are among the most populated, economically valuable, and ecologically productive regions in the United States. Coastal counties, which comprise just 10 percent of the Nation's landmass,[15] are home to approximately 40 percent of the Nation's population (U.S. Census Bureau, 2011) and contributed $6.6 trillion to the U.S. economy in 2011, the most recent year for which data are available (NOAA, 2012b). Coastal areas also support 40 percent of listed endangered and threatened species, including 75 percent of listed mammals and birds (USFWS, 2006 & 2014).

The high concentration of the Nation's population and resources in coastal areas means that impacts to these areas can easily disrupt critical social, economic, and natural systems throughout the United States, disruptions that are likely to become more frequent and/or costly, given the growing risk of harmful climate-related hazards in coastal areas (Burkett & Davidson, 2013).

In most coastal areas, especially those that are densely populated, risk-reduction and resilience strategies have relied heavily on gray infrastructure,[16] such as seawalls, levees, groins, and bulkheads. While generally effective within their design parameters, such approaches can have drawbacks. Gray infrastructure can be expensive to construct and maintain, impede access to certain economic and recreational opportunities, adversely affect surrounding ecosystems, and fail to efficiently address certain coastal hazards. Gray infrastructure also cannot adjust naturally to environmental shifts imposed by climate change or inherently dynamic coastal systems, whereas some types of green infrastructure demonstrate adaptability under changing conditions. For the long term, the prospect of increased

[12] https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_sustaining_environmental_capital_report.pdf.

[13] https://www.whitehouse.gov/sites/default/files/docs/enhancing_climate_resilience_of_americas_natural_resources.pdf.

[14] https://www.federalregister.gov/articles/2015/02/04/2015-02379/establishing-a-federal-flood-risk-management-standard-and-a-process-for-further-soliciting-and

[15] Excluding Alaska (see: http://stateofthecoast.noaa.gov/population/welcome.html).

[16] Also known as "built" or "hard" infrastructure.

shoreline armoring[17] in response to anticipated continuing sea level rise in coming decades also prompts consideration of the coastal legacy our Nation wishes to bestow upon future generations.

Resilience and risk-reduction strategies based on the preservation and/or restoration of natural and/or nature-based coastal features – alone, or in conjunction with non-natural structures in hybrid approaches – can offer alternatives to strategies based solely on gray infrastructure. A substantial body of anecdotal and scientific evidence indicates that certain types of CGI can reduce coastal vulnerability to storms, erosion, flooding, rising sea levels, and similar climate-related hazards. In addition to hazard mitigation, CGI can offer co-benefits that contribute to the economic prosperity and well-being of coastal communities, thereby enhancing community resilience, such as plant and animal habitat, improved water quality, and recreational opportunities that can be leveraged to simultaneously achieve additional social, economic, and environmental objectives (Edwards et al., 2013).

Substantial knowledge and application gaps currently impede more widespread adoption of CGI strategies. Additional fundamental research is needed to enhance models and predictions of natural and human variability in areas including sea-level rise, storm surge, coastal erosion, and degradation of existing coastal ecosystems (USGCRP, 2012). Although CGI has been demonstrably effective at enhancing resilience under certain circumstances, it is clear that the potential and effectiveness of green infrastructure varies across regions, scenarios, and decision contexts. Optimal use of CGI requires a thorough understanding of a community's needs and the ecosystem services (including co-benefits) that are likely to be provided by alternative infrastructure approaches under different conditions, as well as greater consistency in the structure and application of methods used to identify, quantify, and value these services.

1.3 Structure

The report is structured as follows. Section 2 summarizes existing information on major categories of CGI and associated ecosystem services (including co-benefits). Section 3 explains the purpose of, approaches to, and challenges associated with assessing ecosystem services, with a focus on ecosystem services provided by CGI. Section 4 discusses factors that can have significant bearing on the viability and appeal of different infrastructure-based approaches to enhancing coastal resilience, that is, factors that should be taken into account when considering if, when, and how to use CGI in a given setting. Finally and most central to this report, Section 5 recommends areas for prioritized Federal research to support the integration of CGI into risk reduction, resilience planning, and decision making.

[17] The practice of using physical structures – such as seawalls, breakwaters, and riprap – to protect shorelines from coastal erosion.

2. Role of coastal green infrastructure in enhancing resilience

Strategic implementation of CGI (including hybrid approaches) requires knowledge of the range and levels of ecosystem services provided by CGI approaches under various scenarios. Those seeking to integrate CGI into planning and decision making should understand how the ecosystem services (including co-benefits) associated with such approaches can vary under different conditions, across and within distinct geographic regions, and through time. Such understanding is necessary to help planners and decision makers identify circumstances under which CGI approaches are likely to perform well or fail.

There is a substantial and growing body of work investigating the demonstrated and potential role that CGI can play in reducing risk and enhancing coastal resilience. Hurricane Sandy recovery efforts, particularly efforts funded by the Disaster Relief Appropriations Act of 2013, led to significant progress in CGI research and implementation, especially with respect to reducing coastal vulnerability by leveraging ecosystem services provided by CGI that lessen damages associated with storms, erosion, flooding, rising sea levels, and similar climate-related hazards. These specific ecosystem services are herein referred to as "protective services."

The following sections summarize current understanding of the protective services associated with different types of CGI.

2.1 Types of coastal green infrastructure and associated protective services

Several types of CGI provide protective services that can help reduce vulnerability and enhance resilience to coastal climate-related threats (Koch, 2009; Barbier et al., 2011; Axley, 2013). These primarily include, but are not limited to:

- *Salt marshes.* Coastal wetlands that form in saline tidal zones along protected shorelines.
- *Mangroves.* Forests of trees and shrubs that form in tropical and subtropical regions.
- *Reefs.* Ridges of material submerged at or below ocean, estuarine, or river surfaces. Reefs may be biogenic (composed of organisms such as mussels, oysters, and corals) or geogenic (composed of rock, sand, or other inorganic substrates).
- *Seagrass beds.* Submerged aquatic vegetation that grows in shallow marine and estuarine habitats.
- *Sand beaches and dunes.* Deposits of sand and gravel shaped by oceanic waves, wind, and coastal vegetation.

2.1.1 Salt marshes

Wave attenuation. Marsh vegetation and bottom friction in shallow wetlands can attenuate the energy of waves, tides, and currents, thereby reducing the physical impact of low-intensity storms. Salt marshes have a demonstrated capacity to attenuate waves and floodwaters across a range of geographic and hydrodynamic settings, although the degree of attenuation depends on the physical characteristics of the marsh (e.g., species composition of marsh vegetation) and its surroundings (Shephard, Crain, & Beck, 2011; Ferrario et al., 2014). While the majority of studies examining salt marsh wave attenuation have focused on the effect of salt marshes on low- or medium-energy waves (Shephard, Crain, & Beck, 2011; U.S. Army Corps of Engineers, 2014), there is evidence that salt marshes also have the capacity to reduce wave impact during major storms, i.e., weather events characterized by sustained high wind speeds, wave energy, and storm surge (Ferrario et al., 2014; Möller et al., 2014).

Soil stabilization and sediment flow. Given suitable conditions, salt-marsh vegetation can reduce coastal erosion, resulting in stable shorelines that are more effective at buffering wind and waves (Barbier et al., 2011; Shephard, Crain, & Beck, 2011). Sediment deposition and accretion in salt marshes can also help maintain coastal elevation, mitigating the impact of sea-level rise. Sediment deposition and accretion rates are positively correlated with suspended sediment concentrations and proximity to sediment supplies: an important relationship, given that certain types of coastal protective structures, such as sea walls and levees, often decrease sediment availability (Shephard, Crain, & Beck, 2011).

Water flow and flood regulation. Vegetated marshes have greater water uptake and holding capacity than unvegetated mudflats (Barbier et al., 2011). While diking, channelization, and other modifications to natural coastal hydrology can enhance drainage and/or limit coastal inundation, such modifications may have adverse effects on coastal characteristics, including habitat, soil and sediment composition and distribution, and environmental chemistry (Hood, 2004). Natural and restored marshes can promote efficient drainage to reduce storm surge and flooding without such substantial ecosystem impacts (Shephard, Crain, & Beck, 2011). Relevant data captured during and immediately after extreme weather events, however, tend to be sparse and incomplete for these habitats, making it difficult to quantitatively evaluate the impact of salt marshes on moderating water flow during storms.

2.1.2 Mangroves

Although viable mangrove habitat spans a narrower geographic range than does viable salt marsh habitat,[18] the relevant services provided by the two natural features are similar. Important differences are noted below.

Wave and wind attenuation. Mangrove vegetation is taller and therefore generally provides a greater degree of wave attenuation than salt marsh vegetation. Yet, while mangroves can provide some protection from extreme events, such as tsunamis, studies suggest that mangrove wave attenuation remains most effective for storms that generate waves of less than 1 meter in height (Barbier et al., 2011; Coasts at Risk, 2014). Mangrove trees are often tall enough to attenuate wind energy as well. Modeling analyses have shown that mangroves are capable of reducing the height of short-period wind-generated waves[19] by 13 to 66 percent over 100 meters of width, and by 50 to 100 percent over 500 meters (Coasts at Risk, 2014; USACE, 2014).

Soil stabilization and sediment flow. While both the aboveground structures and belowground roots and rhizomes of salt marsh vegetation can play important roles in shoreline stabilization, mangroves primarily stabilize soil and capture sediment through their extensive aboveground root structures (UNEP-WCMC, 2006). Quantitative evaluations of this benefit remain relatively limited.

Water flow and flood regulation. Several case studies have shown that mangroves can reduce flooding from storm surge. In Florida, for instance, mangroves reduced peak storm surge during Hurricanes Wilma and Charley by between 4 and 48 cm per kilometer of mangrove that the surge passed through (Coasts at Risk, 2014). Quantitative evaluations of mangrove capacity to reduce storm surge are,

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[18] Regional warming associated with climate change has expanded the range of mangrove forests. Over the past three decades, for instance, the area of mangrove forests on the east coast of Florida has doubled at the northern end of their historic range. Continued warming may further shift the current geographic boundaries of mangrove forests (Cavanaugh et al., 2014).

[19] Waves generated by wind that succeed each other at short time intervals.

however, generally limited by the lack of necessary real-time data collected during and shortly after extreme weather events.

2.1.3 Reefs

Wave attenuation. A meta-analysis of 27 studies (Ferrario et al., 2014) found that coral reefs consistently reduce incident wave energy by 97 percent, regardless of the intensity of the wave. This decrease in wave energy translates to an average 64 percent reduction in wave height, a performance that compares favorably with average reductions provided by artificial structures such as break waters (Coasts at Risk, 2014). The wave attenuation capacity of other biogenic reefs, such as oyster reefs, has been less examined, though studies are becoming more available. For example, a recent study found that oyster reefs can act as buffers by absorbing wave energy, reducing erosion and trapping suspended sediment (Kroeger 2012).

2.1.4 Seagrass beds

Wave attenuation. Although seagrasses have been shown to reduce wave energy, the limited height of seagrass canopies (generally <50 cm) restricts the wave attenuation capacity of seagrasses to shallow areas. There are few quantitative assessments of this service (Barbier et al., 2011; USACE, 2014).

Soil stabilization and sediment flow. Seagrass roots and rhizomes and accumulated seagrass debris on beaches can stabilize sediment and help control erosion. Again, there are few quantitative assessments of this service (Barbier et al., 2011; USACE, 2014).

2.1.5 Sand beaches and dunes

Wave and wind attenuation. When waves and wind contact the shoreline, their energy is attenuated by the beach face and by sand dunes on the beach berm. The degree of wave attenuation is highly dependent on the morphology and composition of the beach: beaches that are wider, more densely vegetated, and characterized by taller dunes typically provide greater levels of wave attenuation. The complexity of the interactions among various beach characteristics has made it difficult to quantitatively determine the magnitude of wave and wind attenuation provided by sand beaches and dunes (Barbier et al., 2011; USACE, 2014).

Water flow and flood regulation. Beaches and dunes can provide a physical barrier against high water levels but do not prevent back-bay flooding from storm surge that passes through inlets (USACE, 2014).

2.2 Hybrid approaches

Successful coastal resilience strategies frequently require both green and gray infrastructure. Hybrid infrastructure approaches integrate the two by strategically combining non-natural structures with natural and/or nature-based elements. Such approaches can capitalize on the strengths of both types of infrastructure, while compensating for the weaknesses of each (Bouma et al., 2014). Effective use of hybrid infrastructure requires knowledge not only of the unique benefits and tradeoffs associated with particular natural and/or nature-based features and non-natural structures, but also of the synergistic and destructive interactions of green and gray infrastructure when deployed together.

In particular, many types of gray infrastructure have detrimental impacts on natural features and the protective services they provide. Bulkheads, revetments,[20] and other shoreline-hardening approaches

[20] Sloping structures made of wood, sandbags, rocks, or other material placed on banks or cliffs in order to absorb the energy of incoming water.

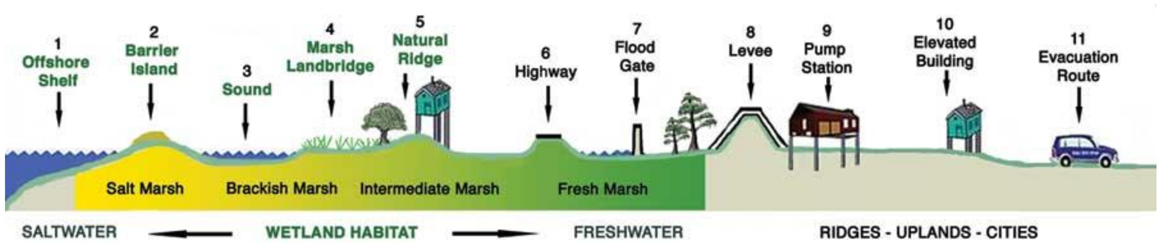
can accelerate shoreline erosion and reduce the intertidal habitat that supports salt marshes and estuarine vegetation. Seawalls, groins,[21] and other offshore armoring can prevent necessary sediments from reaching beaches and coastal wetlands (USACE, 2013). Thoughtful design and engineering may mitigate these consequences. Semi-permeable groins, for example, allow sediments to flow more naturally than non-permeable groins, and have been found to be less harmful to adjacent downdrift beaches (City of New York, 2013). Hybrid infrastructure approaches that allow or mimic natural processes can help planners and decision makers retain the co-benefits provided by natural systems, while minimizing tradeoffs that commonly accompany gray infrastructure.

Further, non-natural structures that are consciously integrated into hybrid approaches can support, rather than impede, provisioning of services by natural features. Gray infrastructure is strongest on the day it is constructed and requires continual maintenance or eventual replacement to offset deterioration caused by the physical impacts of waves and wind. By contrast, green infrastructure can – under suitable conditions – strengthen over time. It is therefore possible to design hybrid infrastructure approaches in which gray components protect green components in the period shortly following implementation, while growth and entrenchment of green components lessen degradation or allow removal of the gray components in the longer term (Sutton-Grier et al., 2015). When deployed strategically, green infrastructure also can absorb wave and wind energy and storm surge so as to extend the life of gray infrastructure and reduce the height and cost required for gray infrastructure to

Box 1. Using "Multiple Lines of Defense" to protect Louisiana's coasts

Strategically combining infrastructure approaches can be an efficient, effective way to protect against climate-related hazards. This idea is gaining traction in areas like Louisiana, where natural disasters such as Hurricanes Rita and Katrina have recently underscored the dangers of relying on single risk-reduction measures, and, conversely, the benefits of deploying multiple types of infrastructure in conjunction with one another. In New Orleans, for instance, overtopped embankments fronted by marshland survived Hurricane Katrina better than those without forward defenses (Government Printing Office, 2006).

The major impacts of these events have accelerated the adoption of a "Multiple Lines of Defense (MLoD)" approach to coastal protection in Louisiana (below). The multiple lines of defense strategy involves using environmental features such as barrier islands, marshes, and ridges to complement structures such as highways, levees, and flood gates, as well as nonstructural measures such as raised homes and evacuation routes. MLoD was proposed as a coastal protection strategy for Louisiana as part of the U.S. Army Corps of Engineers' 2009 Technical Report on Louisiana Coastal Protection. Today, MLoD is a fundamental component of the Louisiana Coastal Protection and Restoration Authority's Flood Risk and Resilience Program, part of Louisiana's Comprehensive Master Plan for a Sustainable Coast.



Depiction of multiple lines of defense strategy. *This example of a hybrid infrastructure approach to coastal protection has been widely adopted in Louisiana. Source: Lake Pontchartrain Basin Foundation.*

[21] A long, narrow structure built out into coastal water from a beach in order to prevent beach erosion.

provide adequate protection from climate-related hazards (USACE, 2004 & 2009; Palmer, 2013) (see Box 1).

Though some studies have been conducted on the ecological tradeoffs associated with hybrid approaches (e.g., Bilkovic et al., 2013), there is still a range of potentially synergistic combinations of green and gray infrastructure options that remains unexplored. Nevertheless, hybrid approaches present promising options for advancing the integration of natural features into coastal resilience strategies. A recent report from The Nature Conservancy found that hybrid approaches can "provide a cost-effective way to reduce flood risks at the neighborhood scale" and that "innovative financing options (e.g., transferable development rights, pay-for-performance contracts, etc.) are available to bring these hybrid approaches to reality" (Freed et al., 2013).

Hybrid approaches are also receiving increasing recognition at the Federal level. For instance:

- The U.S. Army Corps of Engineers supports planning for coastal resilience through an integrated approach that includes natural and hybrid features, as well as non-structural elements (e.g., policy changes or incentives) (Bridges et al., 2013).
- The Rebuild by Design challenge[22] overseen by the Department of Housing and Urban Development (HUD) emphasized the importance of green infrastructure. Rebuild by Design competitively awarded a total of $930 million to support six innovative infrastructure projects designed to enhance coastal resilience in the region affected by Hurricane Sandy. Each of these projects has a significant hybrid infrastructure component.
- The U.S. Climate Resilience Toolkit,[23] released in November 2014 as part of the President's Climate Action Plan and Executive Order 13653, provides a collection of online tools and resources to help the Nation prepare for climate-related changes and impacts (see Box 3 on page Topic 5: Decision support32, including tools and resources that support investigation of which hybrid infrastructure approaches might be most appropriate for a given community or setting.

2.3 Co-benefits

One of the most compelling reasons to use CGI (including hybrid approaches) to reduce coastal vulnerability and enhance resilience is that CGI can provide valuable co-benefits.[24] Indeed, many of the co-benefits associated with CGI are precisely what make coastal areas so valuable, drawing people to live and work in these otherwise risk-prone regions. The salt marshes, mangroves, seagrasses, reefs, beaches, and dunes that enhance coastal 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). Hence, CGI projects implemented for the purpose of reducing vulnerability and enhancing resilience can simultaneously advance other societal, environmental, and economic objectives and can help planners and decision makers better achieve policy and regulatory goals, such as those articulated

[22] More information available at http://www.rebuildbydesign.org/.

[23] Available at http://toolkit.climate.gov/.

[24] Distinctions among "ecosystem services" and "co-benefits" are context-specific and generally determined by the primary management objective(s) at hand. For instance, if an oyster reef was restored for the purpose of buffering storms, then an assessment of the services associated with the restoration might classify the reef's wave attenuation capacity as an "ecosystem service" and the reef's water filtration capacity as a "co-benefit." If the reef was restored to enhance local water quality, however, the classifications could be swapped. In this document, protective services (i.e., services that directly reduce coastal vulnerability to climate-related hazards) are considered the "ecosystem services" of primary interest. For clarity, we refer to other ecosystem services associated with CGI as "co-benefits."

in the Clean Water Act.[25] This is in contrast to certain types of gray infrastructure, which can inhibit the provision of ecosystem services by natural coastal features. Improving capabilities for identifying, quantifying, and valuing ecosystem services (including co-benefits) will help advance approaches that, all else equal, achieve the desired objective(s) while optimizing the delivery of co-benefits and imposing minimal tradeoffs.

2.4 Variability in ecosystem services provided by coastal green infrastructure

Another key consideration for planners and decision makers considering CGI deployment is that in many cases, the ecosystem services (including co-benefits) provided by CGI are variable. Even within a distinct geographic region, the magnitude of ecosystem services provided by a given feature may fluctuate, which can affect the capacity of CGI to help meet desired objective(s). Improvements in the understanding and quantification of variability in ecosystem-service provision are likely to improve the validity of ecosystem-service assessment (Section 3) and lead to better management decisions (Koch et al., 2009). Three prominent sources of variability in the provision of ecosystem services associated with CGI (including hybrid approaches) are explained below.

2.4.1 Non-linear variability

The biophysical characteristics of CGI may be nonlinearly related to the ecosystem services that CGI provides. For example, storm wave height has been shown to decrease quadratically with mangrove forest width (Mazda et al., 1997; Barbier et al., 2008). Other ecosystem-service functions change dramatically at a given point (threshold behavior), level off (asymptotic behavior), or are bounded. The dependence of seagrass wave attenuation capacity on seagrass density exhibits two of these nonlinearities: observable wave attenuation only occurs in seagrass beds of sufficient density, and maximum bed density is bounded by the number of seagrass shoots that can physically fit into a given space (Koch et al., 2009). Accounting for nonlinearities in models of ecosystem-service provision is especially important when such models will be used to predict the effects of ecosystem scaling.

2.4.2 Temporal variability

Natural features may exhibit both periodic and sustained changes with time. Vegetation density in certain natural features fluctuates seasonally (Koch et al., 2009), while reefs may experience longer-term net expansions or decline depending on environmental conditions (Perry et al., 2013). Habitat quality may also improve or diminish over time, depending on external factors such as climate change and coastal development. Poor habitat stresses organisms and reduces biomass production, which in turn may reduce the ability of a natural feature to provide certain ecosystem services, particularly services that help enhance resilience to climate change (Massel et al., 1999). Natural habitat evolution and fluctuation can also lead to improvements for some species and degradation for others. Furthermore, the provision of ecosystem services by green infrastructure depends on how long the infrastructure has had to reach maturity, how well it has been maintained, and other time-dependent factors (EPA, 2013; NOAA, 2014). Accurate assessment and forecasting of these and other dynamic features requires consideration of time-dependent variables (Koch et al., 2009).

2.4.3 Spatial variability

Both coastal features and hazards are physically heterogeneous. A salt marsh may contain both densely and sparsely vegetated areas within its boundaries, and wind speeds vary across the span of a hurricane. Physical heterogeneity inevitably results in spatial variability of the ecosystem services provided by

[25] http://www2.epa.gov/laws-regulations/summary-clean-water-act.

natural features. In some cases, the spatial variability of the natural feature characteristic(s) of interest may be limited enough that the average value of the characteristic(s) may be a reasonable proxy for the exact values. In others, higher-resolution, location-specific data may be needed in order to appropriately account for spatial variability and perform an accurate analysis (Costanza et al., 2006).

2.5 Key takeaways

- There is strong evidence that CGI (including hybrid approaches) can provide protective services that help enhance resilience and reduce vulnerability to coastal hazards.
- Additional work must be done in order to rigorously document, understand, and model these and other services (i.e., co-benefits) associated with CGI, as well as the biophysical, spatial, temporal, and other factors that affect service delivery.
- There is a need to develop clearly defined and widely accepted sets of metrics and mathematical expressions (i.e., “ecological production functions”, discussed more fully in Section (3)) to facilitate characterization and analysis of the effects of changes in the structure, function, and dynamics of an ecosystem.
- There is also a need to increase understanding of key aspects of CGI that have been understudied and/or are currently poorly understood, e.g., overall performance of CGI and hybrid approaches, including the co-benefits provided under various scenarios, how such approaches perform under extreme conditions, sediment and water flow patterns across different types of infrastructure, and how variability and uncertainty can be accounted for in a decision-making context.

3. Role of ecosystem-service assessment

Recognition and understanding of the biophysical components of CGI are necessary but not sufficient prerequisites for the broad integration of CGI (including hybrid approaches) into coastal resilience and risk-reduction strategies. To justify the use of CGI, planners and decision makers also need information demonstrating that marginal changes in the provision of associated ecosystem services (including co-benefits) are worth the necessary investments and tradeoffs. This section explains the rationale for integrating ecosystem-service considerations into planning and decision making, the broad components that may be involved in carrying out an ecosystem-service assessment, and common challenges. The section also includes a discussion of how a class of techniques known as "benefit transfer" can help facilitate consideration of ecosystem services, and identifies information most needed by decision makers in order to effectively integrate ecosystem-service considerations into evaluation of CGI approaches.

3.1 Rationale for assessment

Integrating ecosystem-service considerations into planning and decision making generally requires one or more of the following:

- Qualitative identification and description of significant ecosystem services associated with the entity under consideration.
- Quantitative examination of marginal changes in service provision,[26] particularly through development and application of ecological production functions.
- Valuation of marginal changes, including monetary and non-monetary approaches.

In practice, efforts to carry out any of these activities often raise questions about, among other topics, the best way to ensure that all significant ecosystem services – including intangible services such as cultural or aesthetic benefits – are fully and appropriately considered; assign values, especially monetary values, to benefits that are not directly traded in markets; and integrate qualitative, quantitative, and monetized information on ecosystem service values in a way that facilitates meaningful comparison.

There are also concerns that promoting systematic assessment of ecosystem services may cause society to adopt an increasingly utilitarian view of the human-nature relationship, with the result that the ethical, aesthetic, and other intrinsic values of nature are of little or no import in decision making (TEEB, 2010). Indeed, studies indicate that recognition of economic incentives may undermine conservation goals (Bowles, 2008).[27]

Keeping these concerns in mind, there are several compelling reasons to develop and improve methodologies for integrating ecosystem services into planning and decision making. Absent active efforts to recognize, describe, quantify, and, where appropriate, monetize ecosystem services, the value of these services and the natural resources that provide them may default to zero in benefit-cost analyses and other decision-support processes. Undervaluing a natural resource, whether in a formal benefit-cost analysis or in routine daily actions, leads to suboptimal use of that resource, including over-exploitation and degradation. In the Federal context, many statutes, regulations, and mandates require economic analysis to inform investment in, design of, and permitting for a variety of projects, including

[26] The effect of the next incremental unit of change on production.

[27] For a more detailed discussion on this topic, see *Ecological and Economic Foundations* (TEEB, 2010).

coastal infrastructure projects.[28] Methodologies for assessing ecosystem services can facilitate inclusion of the full range of benefits provided by CGI in such analyses (EPA, 2010; TEEB, 2010).

Ecosystem-service assessment can also help support efficient allocation of resources. Competitive economies use markets to channel resources to their optimal use; well-developed markets, however, currently exist only for a limited subset of coastal ecosystem services. This subset is comprised almost exclusively of "provisioning services," such as the supply of seafood, materials, and other resources directly used by humans (although in areas that have implemented tradable permits,[29] "regulating services" such as water quality may also be included). Certain approaches for assessing ecosystem services can provide information on the relative worth of the broad range of ecosystem services that are not readily marketable, helping planners and decision makers allocate resources appropriately (TEEB, 2010; Ninan, 2014).

Finally, integrating ecosystem-service considerations into planning and decision making can help draw attention to the many critical contributions natural systems make toward improving the productivity, resilience, and livability of our Nation and communities. These contributions are often discounted and/or disregarded. As a global study of ecosystem and biodiversity economics observes, ecosystem-service assessment, including ecosystem-service valuation, "can serve as a tool…which helps people rethink their relations to the natural environment and increase knowledge about the consequences of consumption choices and behavior for distant places and people" (TEEB, 2010). Taking ecosystem services into account allows a better understanding of the complex relationships between the economic, social, and environmental realms of our world, helping people make better choices and avoid unintended or unforeseen consequences (EPA, 2014).

The following sections summarize some of the most widely accepted approaches and recognized challenges to integrating ecosystem-service considerations into planning and decision making. Several important points apply here:

- There is extensive literature but relatively limited consensus on how best to assess the significant ecosystem services in an area of interest. The discussion presented below provides a broad overview of the steps that may be included in an ecosystem-service assessment, associated considerations, and example methodologies most relevant to CGI.
- There is no single or best approach for assessing ecosystem services provided by CGI. The approach used to assess a particular project should be tailored to project characteristics and decision needs.
- In examining ecosystem services, it is important to distinguish between "outputs" (i.e., goods or services produced by an entity) and "outcomes" (i.e., the results or consequences of an action that are of direct importance to beneficiaries and the broader public, and may be associated with a change in one or more outputs). While outcomes are generally more relevant to planners and decision makers than outputs, outputs are more directly measurable and must often be quantified in order to establish a causal link between actions taken and outcomes achieved. Some methodologies can help establish this link.
- While certain methodologies for examining ecosystem services can facilitate meaningful comparison of substantially different goods and services, all incommensurable values generated

[28] For examples, see Chapter 2 of EPA's *Guidelines for Preparing Economic Analyses* (EPA, 2010), as well as the "Assessment Framework" of the Federal Resource Management and Ecosystem Services Guidebook (National Ecosystem Services Partnership, 2014).

[29] For instance, point-source permits issued under the National Pollutant Discharge Elimination System (NPDES) Program to achieve Total Daily Maximum Load (TMDL) requirements.

in an assessment should be examined, retained, and presented separately in order to ensure transparency and accuracy (EPA, 2010; TEEB, 2010).[30] Practitioners should be aware of the potential for information loss and other pitfalls in approaches for integrating ecosystem services into planning and decision making that reduce "different types or dimensions of value…to a single rod of measure" (TEEB, 2010).

3.2 Components

As stated above, integrating ecosystem-service considerations into planning and decision making may require qualitative identification and description, quantitative examination, and valuation of all significant ecosystem services in an area of interest, although not all of these activities may always be appropriate or necessary. This section provides a broad overview of current understanding and practice of each of these general components.

3.2.1 Qualitative identification and description

The first stage in integrating ecosystem-service considerations into planning and decision making generally involves qualitative identification and description of significant ecosystem services, including tangible goods and benefits (such as the provision of food and materials), regulating and protective services (such as carbon sequestration or flood control), recreational opportunities, and cultural and aesthetic benefits, associated with the feature, project, region, or other entity under consideration. Expert consultation and reference to ecosystem-service studies conducted in similar contexts can help ensure that all relevant services are appropriately captured in this stage. Eliciting community feedback through interviews, focus groups, and other tools and techniques is particularly valuable in helping to draw attention to some important services that might otherwise be overlooked.

3.2.2 Quantitative examination

The bulk of the work involved in assessing all significant ecosystem services in an area of interest focuses on quantitative examination of marginal changes in service provision (Millennium Ecosystem Assessment, 2003). This generally requires integrating and analyzing relevant data in order to generate production functions, i.e., mathematical expressions that estimate the effects of changes in the structure, function, and dynamics of an ecosystem on outputs that are directly relevant and useful to decision makers (USACE, 2015). For example, biophysical data could be used to develop a production function relating height of inland storm surge to area of coastal wetland contacted. A major consideration in development of ecosystem-service production functions is the availability of sufficient data and metadata to generate production functions that are reliable and consistent across a range of settings.

3.2.3 Valuation

Qualitative and quantitative assessment of ecosystem services can facilitate valuation of marginal changes in these services. Valuation can be carried out using monetary and qualitative and quantitative non-monetary approaches. Monetary valuation approaches, which yield values in dollar terms, include:[31]

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[30] Detailed guidelines for the presentation of economic analysis and results can be found in Chapter 11 of EPA's *Guidelines for Preparing Economic Analyses* (EPA, 2010).

[31] Adapted from Murray et al., 2014.

- *Market-based approaches*. Use evidence from market transactions to indicate the value of outputs of natural systems. Market-based approaches value ecosystem goods and services that are directly or indirectly used by humans.
- *Non-market-based approaches.* Generate estimated values when there is no explicit market for an ecosystem good or service (Champ et al. 2003; Freeman 2003; NRC, 2005). There are two types of non-market-based approaches:
    - *Revealed-preference approaches.* Observe behavior in markets for goods or services related to the ecosystem of interest to determine value (Herriges and Kling, 1999; Bockstael and McConnell, 2007). For instance, a revealed-preference approach called the hedonic price method can be used to assess the value that a beach (the ecosystem good) contributes to a home value (the related good) by regressing home prices against beach proximity and other relevant variables in order to parse out the individual contribution of the beach to home price. Revealed-preference approaches result in estimates of the marginal change in the value of ecosystem goods and services that are directly or indirectly used by humans.
    - *Stated-preference approaches.* Use information on what people say in response to carefully constructed questions (often posed in surveys or interviews) to determine the worth that individuals place on marginal changes in individual ecosystem goods and services (Mitchell and Carson, 1989; Hanley et al., 1998; Alpizar et al., 2001; Kling et al., 2012). One type of stated-preference method, the choice experiment method, involves asking individuals to choose between alternatives that differ in several attributes, such as size, storm protection provided, and cost involved. Responses to these questions are analyzed in regression models to reveal the marginal values of changes in the attributes. Stated-preference approaches are most appropriate for valuing ecosystem goods and services that are not directly used by humans.

There are numerous examples of monetary valuations for many of the services provided by CGI (see, for instance, Costanza et al., 2006; Batker et al., 2010; Barbier et al. 2011; Moser et al., 2012; Abt Associates, 2014; Barbier & Enchelmeyer, 2014). Monetary valuation of marginal changes is attractive in that it generates intuitive, easily communicated, and easily used measures of value, but this method is not always possible or appropriate. For instance, guidance[32] issued by the Office of Management and Budget (OMB) for adhering to the requirements of Executive Order 13563,[33] Executive Order 12866,[34] and OMB Circular A-4[35] cites human dignity, equity, and privacy as examples of benefits for which monetization may not be feasible.

Researchers have developed other valuation approaches that can be used in lieu of, or to complement, monetary valuation. Such approaches methodically apply tools and techniques to integrate disparate qualitative and/or quantitative (i.e., non-monetary) information in a way that facilitates meaningful comparison. Examples include:

[32] "Regulatory Impact Analysis: A Primer" (http://www.whitehouse.gov/sites/default/files/omb/inforeg/regpol/circular-a-4_regulatory-impact-analysis-a-primer.pdf).

[33] "Improving Regulation and Regulatory Review." (http://www.reginfo.gov/public/jsp/Utilities/EO_13563.pdf).

[34] "Regulatory Planning and Review." (http://www.reginfo.gov/public/jsp/Utilities/EO_12866.pdf).

[35] http://www.whitehouse.gov/sites/default/files/omb/assets/omb/circulars/a004/a-4.pdf.

- *Choice modeling*. Statistical analysis of the choices individuals make between bundles of goods and services under different hypothetical or real-world scenarios.[36]
- *Delphi surveys*. An iterative communication process that collects and refines group judgments of a set of experts under the guidance of a facilitator.
- *Q-methodology*. A type of factor analysis used to systematically study and categorize individual viewpoints.
- *Source analysis*. Systematic examination of non-consultative resources such as data, statistics, and documents.

These and other types of non-monetary valuation have long been used to help inform some areas of environmental policy (e.g., delineating protected areas), and have attracted increasing recognition, interest, and research over the last decade (Kelemen et al., 2014).

3.2.4 Reporting

As previously stated, integrating ecosystem-service considerations into planning and decision making does not always require all of the three broad components described above. OMB advises that when conducting a benefit-cost analysis for a proposed regulatory action:

> "…benefits and costs should be quantified and monetized to the extent possible, and presented in both physical units (e.g., number of illnesses avoided) and monetary terms. When quantification of a particular benefit or cost is not possible, it should be described qualitatively. The analysis of these alternatives may also consider, where relevant and appropriate, values such as equity, human dignity, fairness, potential distributive impacts, privacy, and personal freedom."[37]

This is consistent with the National Environmental Policy Act (NEPA, 40 CFR § 1502.23), which emphasizes that in an environmental impact statement, "the weighting of the merits and drawbacks of the various alternatives need not be displayed in a monetary cost-benefit analysis, and should not be when there are important qualitative considerations."

Whether or not quantitative and/or monetary assessments are conducted, review and reporting of relevant ecosystem services should be as systematic and comprehensive as possible. Care should be taken to present the results of an ecosystem-service assessment objectively, accurately, and completely, without disproportionately weighting relevant services that can be quantified and/or monetized over those that cannot. These points are emphasized in the Administration's recently completed Principles, Requirements, and Guidelines for Water and Land Related Resources Implementation Studies,[38] as well as in EPA's *Guidelines for Preparing Economic Analyses* (2010), which state:

> "Ideally, all benefits and costs of a regulation would be expressed in monetary terms, but this is almost never possible because of data gaps, unquantifiable uncertainties, and other challenges. It is important not to exclude an important benefit or cost category…even if it cannot be placed in dollar terms. Instead, such benefits and costs should be expressed quantitatively if possible (e.g., avoided adverse health impacts). If important benefit or cost categories cannot be expressed quantitatively, they should be discussed qualitatively (e.g., a regulation's effect on technological innovation)."

EPA's *Guidelines* also include recommendations for presenting and communicating the qualitative, quantitative, and monetized results of an ecosystem-service assessment in an integrated format that is

[36] This approach is similar to stated-preference choice experiments, with the difference that choice modeling does not include a cost or price attribute. Hence choice modeling precludes estimation of economic values, but does allow evaluation of tradeoffs among the choices available.

[37] "Regulatory Impact Analysis: A Primer."

[38] Available at http://www.whitehouse.gov/administration/eop/ceq/initiatives/PandG.

clear and meaningful, and for maintaining all significant benefit and cost considerations into the decision phase.[39]

3.3 Challenges

There remain persistent challenges to the biophysical and economic assessment of ecosystem services. Some of the major challenges that may affect practical assessment of ecosystem services – specifically, ecosystem services related to coastal resilience – are described below.

3.3.1 Data coverage and quality

Robust examination of ecosystem services depends on the availability of high-quality, relevant data: in particular, biophysical data used to generate ecological production functions. Rigorous data collection can be expensive and time-consuming and requires forethought and planning in order to ensure consistent collection practices and establish a reliable baseline against which to compare future developments. High-quality scientific data are hence only available for a limited subset of ecosystem services (including co-benefits) associated with CGI (Box 2). 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 are also generally sparse data on ecosystem-service delivery and value during extreme-weather events, due to the relative infrequency of major storms and the high cost of data-collection hardware able to function in severe conditions. These generalities notwithstanding, there is substantial geographic variation in the nature and quality of ecosystem-service data available, which in turn leads to substantial regional variation in the ecosystem-service studies that have been carried out for CGI (National Research Council, 2014).

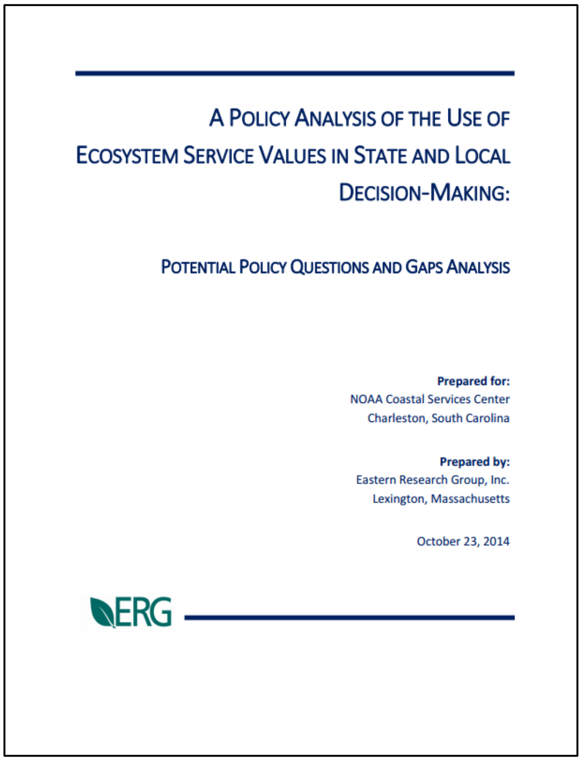
3.3.2 Individual knowledge and response

Most protective services provided by CGI are not traded in markets, though there are some specially designed markets for ecosystem services (e.g., for carbon emission credits). Integrating these services into planning and decision making therefore often includes stated-preference studies, the results of which can be highly dependent on study design (e.g., population surveyed, question format, characterization of resource under consideration, etc.) (NRC, 2005; TEEB, 2010). For instance, individuals who are unaware of the substantial carbon sequestration benefits provided by coastal wetlands may unintentionally understate their willingness to pay for wetland preservation and restoration. Individuals who are unaware that wetland preservation and restoration could impede access to certain coastal recreational opportunities, on the other hand, may unintentionally overstate the same.

Furthermore, an individual may face perverse incentives to consciously conceal his or her true perspectives. If an individual believes that a stated preference survey will be used to determine tax rates or ecosystem use fees, then that individual may alter his or her responses accordingly. Individual willingness to pay for an ecosystem service also depends on how much disposable income that individual has for mandatory or discretionary expenditures. All these challenges in the use of stated-preference techniques are well understood and accounted for in survey design and analysis (NRC, 2005; TEEB, 2010). However, the uptake of results from these studies to help direct policy and decision making is still in a formative stage (see Box 2).

[39] See Chapter 11 of the *Guidelines*.

Box 2. Improving the integration of ecosystem-service values in state and local decision making



A Policy Analysis of the Use of Ecosystem Service Values in State and Local Decision-Making:

Potential Policy Questions and Gaps Analysis

Prepared for:
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October 23, 2014

ERG

A recent NOAA-funded study (ERG, 2014) reviewed the current state of information on estimated monetary values of ecosystem services and identified policy questions that could be answered using this information. The study found that while many planners and decision makers are interested in the concept of ecosystem service assessment, gaps in coverage of coastal ecosystem services limit the extent to which these key stakeholders can integrate ecosystem service values into coastal policy and management. For example, economic value estimates are readily available for mangrove and coral reef ecosystems, as well as for recreation-related aspects of beach ecosystems, but not for many services provided by wetlands and other ecosystems. The study also found that planners and decision makers, especially those at state and local levels, need further guidance on how to appropriately use the results of ecosystem service assessments. This would include clear definitions of key terms, detailed steps on how to generate, interpret, and apply estimates of ecosystem-service values, information on where and how to access needed economic expertise, and descriptions of case studies and examples to which state and local policymakers can relate.

3.3.3 Changes in supply and demand

Ecosystem services are, by definition, anthropocentric. The value of an ecosystem service is determined by human demand for that service vis-à-vis supply. This value may change if natural features are destroyed or restored, there are changes in substitute or complementary goods, or preferences evolve due to changes in public knowledge and opinion.[40] For example, the value of salmon habitat will increase if a public advertising campaign highlights the health benefits of eating salmon (leading to increased demand for salmon stocks) or if a major salmon fishery becomes polluted and collapses (leading to reduced supply). Ecosystem-service valuations – like many biophysical studies – generate results for a set point in time, meaning that they can quickly become obsolete as conditions evolve.

3.4 Benefit transfer

As discussed above, robust ecosystem-service data and studies only exist for a limited subset of ecosystem services and geographic regions. Data and knowledge gaps make it difficult for researchers to examine the services provided by natural features across a comprehensive range of scenarios. Even

[40] The potential for preference changes is often referred to as a "shifting baseline."

when sufficient data exist for rigorous assessment of ecosystem services, carrying out the assessment involves significant time, expertise, and expense.

Although primary data and studies provide the most accurate information on the role of a specific feature in a specific area, benefit transfer (also known as value transfer) techniques may, in certain circumstances, serve as acceptable alternatives when resource (including, for instance, time, money, and technical expertise) or logistical obstacles to primary valuation proves insurmountable (Ninan, 2014).[41] Benefit transfer is the process of applying the monetary values estimated in existing empirical studies to assess the value of a quantified effect in a different study (EPA, 1999). It is built on the idea that if someone has already invested the necessary resources to value a benefit somewhere, that value can be used to help estimate the value of the same benefit elsewhere (Bridges et al., 2015). Benefit transfer techniques include:[42]

- *Functional transfer*. Use of statistical models based on information aggregated from many primary studies to assess an unstudied site, controlling for project characteristics, site features, and location differences. This approach is comparable to statistically examining data on local home sales to appraise the value of a property.
- *Point transfer*. Direct application of single values (usually study averages) to an unstudied site, ideally with social and environmental conditions very similar to those of the original study.
- *Per-acre value transfer*. Valuation of an ecosystem in a given location based on the average assessed value per acre of that ecosystem in other locations. This technique may be acceptable when the value of a service is global in nature (e.g., carbon sequestration) but is generally not sensitive enough when the value of a service depends on the characteristics of local beneficiaries and availability of substitutes (e.g., recreation).

Sophisticated benefit-transfer techniques, like functional transfer, generally outperform simpler alternatives (Bridges et al., 2015). Accurate functional transfer, however, relies on the availability of multiple, rigorous primary studies, which, as previously observed, may be time- and resource-intensive to conduct. Developing robust functional transfer models also requires effort, care, and expertise. Additional investment into data sharing and data interoperability will support development of functional transfer models for planning and decision making. Existing computer tools, programs, and databases that have been designed to facilitate functional and point transfer should be reviewed to determine their applicability to coastal ecosystems.

3.5 Key takeaways

- Integrating ecosystem-service considerations into planning and decision making may require qualitative identification and description, quantitative examination, and/or valuation of all significant ecosystem services in an area of interest. Not all of these components may be necessary and/or appropriate in a given scenario.

- Ecosystem-service assessment generally depends on understanding of the factors that drive demand for and supply of significant ecosystem services in an area of interest, and availability of ecological production functions that facilitate quantitative examination of service provision.

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[41] For more information on the conditions under which a benefit transfer approach is valid, see Richardson et al. (2014) and Johnston and Rosenberger (2010).

[42] List is adapted from Murray et al., 2014:

- There is a pressing need for additional research into best practices for ecosystem-service valuation, particularly with regard to widely-accepted valuation methodologies that are not dependent on market transactions, as well as the valid use of benefit transfer to reduce the intense resource and logistical requirements of appropriately accounting for ecosystem services in planning and decision making.
- Ultimately, the results of any ecosystem-service assessment should be delivered in a way that facilitates integration into planning and decision making, including systematic consideration and comparison of alternative approaches.

4. Integrating CGI and ecosystem services into decision making

Efficiently and effectively addressing coastal vulnerability and enhancing resilience to climate change requires a variety of approaches. Not every approach is suited to every location or objective, and robust climate resilience strategies generally include multiple parts that are often complementary but may also conflict. Advancing broad integration of CGI across climate resilience strategies will require awareness of, and information on, key factors that planners and decision makers should take into account.

Listing, describing, quantifying, and valuing the ecosystem services provided by CGI are critical steps in determining whether coastal green and hybrid approaches for enhancing resilience are suitable to a given context. A crucial remaining step is integrating the results of ecosystem-service assessments into broader planning and decision-making frameworks in order to inform strategic selection among resilience and risk-reduction alternatives. While an exhaustive discussion of decision-making processes is beyond the scope of this document, understanding key factors that are often included in decision-making contexts is a critical part of efforts to advance CGI implementation and assessment. These factors include:

- *Management objectives*
- *Site characteristics and scale*
- *Socioeconomic considerations*
- *Policy directives*
- *Time-dependent considerations*
- *Tradeoffs*
- *Financing*

4.1 Management objectives

Decision makers who share an overarching management goal – such as enhancing coastal resilience – will not necessarily share intermediate management objectives. These objectives are generally shaped by factors unique to the region or project under consideration. For instance, reducing storm surge is more likely to be a priority objective for stakeholders in low-lying, easily-flooded coastal regions, while buffering intense winds is more likely to be a priority objective for stakeholders in elevated coastal regions.

Careful articulation of intermediate management objectives is a key component of decision making related to coastal resilience planning, since intermediate objectives help determine appropriate green, gray, and/or hybrid infrastructure approaches to pursue. Similarly important is the identification and use of assumptions, metrics, and models that can help assess the degree to which various approaches help advance intermediate objectives in question, as well as the degree to which progress towards intermediate objectives represents progress towards the broader goal. Vulnerability maps and other data-visualization tools can help inform the selection of appropriate intermediate objectives, infrastructure approaches, and evaluation metrics. This in turn can help coastal planners and decision makers balance resilience and vulnerability to climate change with other issues such as economic growth, environmental quality, historical preservation, and more. Appropriate objectives, approaches, and metrics can also help planners and decision makers coordinate local priorities and perspectives with priorities and perspectives at the ecosystem, agency, regional, and/or national levels.

4.2 Site characteristics and scale

The physical characteristics of a site can limit options for infrastructure development on that site. Coastal bathymetry, geomorphology, fetch,[43] weather, climate, and other site-specific physical characteristics can affect the biophysical performance of certain types of CGI, and thus some CGI approaches will be more appropriate in some locations than in others. Seagrass beds, for instance, only provide noticeable wave-attenuation benefits in shallow coastal waters (Shepard et al., 2011). Spatial constraints can also limit the viability of green infrastructure; salt marshes and other expansive natural features are poorly suited to densely populated, steep, and/or narrow shorelines, and for some management objectives, larger swaths of open space may be needed for CGI to be successful. Although the physical characteristics of some sites may be mutable if necessary, in general, coastal planners and decision makers at Federal, state, and local levels should strive to identify the approaches best suited to a particular possible project site.

4.3 Socioeconomic considerations

Despite persistent perceptions that coastal communities are predominantly wealthy, the socioeconomic distribution of U.S. coastal populations varies widely (Moser et al., 2014). Indeed, coastal areas exhibit some of the most pronounced income gaps in the country (Global Insight, Inc., 2014). Socioeconomic considerations are highly relevant to coastal climate planning and should be included in decision-making processes. An example from the National Academies (NRC, 2014) illustrates the importance of accounting for such considerations in benefit-cost analysis:

> "…the rich often get greater weight in benefit-cost analysis simply because they have more money. For example, consider a coastal risk reduction project for a community with 10 homes each worth $1 million versus another coastal risk reduction project for 50 homes each worth $100,000. The first project reduces the risk to property worth $10 million while the second reduces risk to property worth $5 million. If both projects cost the same amount of money, benefit-cost calculations would favor doing the first project over the second. However, many observers would favor the second project over the first, in part because it affects more people and the people affected may have less ability to cope with loss."

Coastal restoration and infrastructure investments can impact socioeconomic inequalities. When a large portion of disadvantaged households is supported by resource-dependent industries, such as fishing, protection and restoration of natural features can decrease local income gaps. Restoration projects that protect against coastal hazards may also particularly benefit low-income households, which are less likely to have hazard insurance and thus more likely to benefit from additional measures to reduce the risks of coastal hazards (Moser et al., 2014).

4.4 Policy directives

Some policy directives may affect the integration of green and hybrid infrastructure into coastal resilience planning and decision making. Permitting laws and practices, for instance, make it easier to use gray infrastructure for coastal stabilization than to use green infrastructure. Separate shoreline projects typically require separate Clean Water Act 404 permits[44] to move forward. By contrast, current regulation allows simultaneous approval of multiple infrastructure projects in the same coastal zone with a single U.S. Army Corps of Engineers Nationwide Permit, as long as the projects are "similar in nature." This favors conventional and relatively standardized infrastructure approaches such as bulkheads, for which there are often pre-existing engineering templates and resources, over more novel

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[43] The distance traveled by wind or waves across open water.

[44] http://water.epa.gov/lawsregs/guidance/cwa/dredgdis/.

green infrastructure approaches such as living shorelines, for which project specifications vary from site to site. The integrated nature of living shorelines and many other green infrastructure projects means that implementing such projects may require greater coordination with other regulatory bodies and resource agencies, to support use of green infrastructure where such use would be beneficial.

4.5 Temporal and spatial considerations

Climate change, population shifts, and other time-dependent considerations also are key to informing near-term planning. Many green infrastructure approaches have a natural ability to adapt (to an extent) to the sustained effects of climate change and to respond dynamically to certain episodic disturbances. As long as there is adequate space, salt marshes, mangroves, seagrasses, and some reefs can migrate inland, thereby maintaining coastal stability and resilience with little or no human investment. While severe storms may damage wetland productivity through erosion, vegetation stripping, and/or salinity burn, evidence also suggests that wetlands can incorporate additional mineral sediment deposited by storms, and in doing so become more resilient to future stresses (Bridges et al., 2013). It is important to remember, however, that the time required for vegetation to grow and/or rebound can delay or fully inhibit realization of the biophysical and economic benefits of these adaptive capacities. For instance, if a rate of sea-level rise greater than the inland-migration rate of coastal vegetation may overwhelm the adaptive capacity of coastal vegetation, resulting in the elimination of intertidal habitat (Cahoon et al., 2009).

Space constraints have made it difficult to fully capitalize on the adaptive capacities of green infrastructure. The number of people living in U.S. coastal regions has grown by approximately 40 percent since 1970 (U.S. Census Bureau, 2011). Average coastal population density today is over four times higher than average population density for the United States overall, and is expected to rise steadily over the next decade (Woods & Poole, 2011; NOAA, 2012b). Such trends present a challenge, as growing coastal populations increase vulnerability and risk while also reducing the space available for protective green infrastructure. Coastal planners and decision makers seeking an alternative to gray infrastructure have increasingly begun turning to hybrid resilience strategies to help reconcile competing space needs for green infrastructure and coastal development.

4.6 Tradeoffs

Ultimately, as is also true of gray infrastructure and other resilience approaches, the implementation, existence, and maintenance of CGI will often require tradeoffs that need to be systematically considered. For instance:

- Some CGI projects may replace mudflats and submerged aquatic vegetation with other types of vegetation and habitat, altering the structure and function of the local ecosystem (Coastal Green Infrastructure Research Plan, 2014). Some CGI projects may also rely on non-native vegetation, with potentially detrimental effects.
- Dredging for material to support beach nourishment programs can damage source ecosystems (City of New York, 2013).
- Though green infrastructure can provide a less expensive alternative to gray infrastructure under appropriate circumstances, realization of these cost savings may depend on strategic planning and maintenance (EPA, 2013).
- It takes time for vegetation to grow and/or rebound, meaning that there may be a significant time lag between installation or restoration of a CGI project and associated ecological and economic benefits.

Evaluation and inclusion of these tradeoffs is critical to informed coastal management. As is true of any approach to reducing vulnerability and enhancing resilience, it is practical and important for planners and decision makers to identify and pursue approaches that, all other things equal, achieve the desired objective(s) while optimizing the delivery of co-benefits and imposing minimal tradeoffs. Approaches such as least-cost analysis[45] may be helpful in determining the best approach for a given scenario.

4.7 Financing

The structure and availability of financing for CGI can limit the feasibility of CGI processes. While finance structure and availability will vary across projects, key aspects of financing (e.g., potential short- and long-term financing mechanisms, equity, political viability, and fundraising potential) should be integrated into CGI planning and decision making early on.

A recent guide released by the World Resources Institute details actionable strategies for financing certain green infrastructure projects for source water protection in the United States (Gartner et al., 2013). These include specialized bonds, land acquisition, conservation easements, and enhanced land management practices. Though legal and jurisdictional considerations are different along our nation's coasts (see, e.g., NOAA 2012, Bernd-Cohen et al. 1998), many of these lessons nevertheless apply in general. Careful estimates and sensitivity analyses can be used, in the absence of perfect information, to inform and attract short and long-term investments into green infrastructure projects, and innovative and cost-effective financing mechanisms are increasingly open to these types of investments. Planners and decision makers should seek to identify and assess these and other potential options for financing proposed CGI projects as part of standard planning and decision-making processes.

4.8 Key takeaways

- Optimal use of CGI requires understanding of how the services and tradeoffs associated with CGI fit into broader decision-making contexts.
- Such understanding in turn requires interdisciplinary research to understand and predict how linkages among biophysical, socioeconomic, and behavioral dynamics affect delivery of relevant ecosystem services, tradeoff decisions, and pursuit and realization of desired societal outcomes.
- The development of decision-support tools and other resources can facilitate transition of CGI from research and development to implementation and operation.

[45] Least-cost analysis is a method of comparing costs across alternative actions while holding the level of the outcome constant. This might be an appropriate approach, for example, when the level of outcome is predetermined by statute or for some other reason.

5. Research recommendations

As demonstrated in the preceding chapters, CGI can effectively enhance coastal resilience, reduce vulnerability and risk, and deliver a host of valuable co-benefits. Under appropriate circumstances, coastal green and hybrid infrastructure may present viable or superior alternatives to more conventional gray infrastructure.

Yet current scientific knowledge and public understanding and acceptance of the ecosystem services (including co-benefits), tradeoffs, and other factors associated with the use of CGI is far from complete. To advance the use of CGI and ecosystem-service assessment in enhancing the resilience of our Nation's coasts, the CGIES Task Force recommends that Federal departments and agencies coordinate and collaborate on priority research needs under five topics:

> **Topic 1: Metrics.** How can significant changes in relevant inputs, outputs, and outcomes associated with CGI be measured?
>
> **Topic 2: Production functions.** How can capacities be improved for estimating the effects of changes in the structure, function, and dynamics of ecosystems connected to CGI on outputs that are directly relevant and useful to decision makers?
>
> **Topic 3: Ecosystem-service valuation.** What is needed to facilitate monetary and non-monetary valuation of ecosystem services associated with CGI?
>
> **Topic 4: Social factors.** How do key socioeconomic and behavioral factors affect delivery of ecosystem services provided by CGI? How do linkages among biophysical, socioeconomic, and behavioral dynamics affect broader ecological, economic, and social outcomes?
>
> **Topic 5: Decision support.** What strategies can be used to provide stakeholders with the information and tools they need in order to include ecosystem-service considerations in decision-making processes?

Such research should be conducted in a way that facilitates uptake and implementation of findings (i.e., the "research-to-operations" transition), iteratively incorporates new knowledge and responds to demonstrated needs (i.e., the "operations-to-research" transition), and emphasizes measurement of "on-the-ground" impacts on enhancing resilience. Many of these recommendations are also relevant and applicable to non-coastal settings. Federal agencies should, where possible, ensure that efforts carried out in response to these recommendations align with work and guidance on green infrastructure and ecosystem services more broadly.

These research recommendations are complementary but independent, and are not listed in priority order.

Topic 1: Metrics

Objective, transparent evaluation and comparison of gray, green, and hybrid coastal infrastructure approaches requires clearly defined and widely accepted science-based sets of metrics for assessing significant changes in relevant biophysical, socioeconomic, and behavioral inputs, outputs, and outcomes. Such metrics would help increase the accountability of both established and planned coastal infrastructure projects, while simultaneously facilitating analysis of alternatives for proposed projects and prioritization of investments. Substantial work has already been done to identify metrics that could apply to various types of coastal infrastructure approaches, including the Federal Flood Risk Management Standard, the 2015 *Use of Natural and Nature-Based Features (NNBF) for Coastal*

Resilience report from the U.S. Army Corps of Engineers, and various efforts under the Department of the Interior's Metrics Expert Group (MEG). Future efforts should focus on synthesizing and expanding this work and developing it into resources that researchers and decision makers can easily access and use.

Priority research needs

(a) **Review and synthesize existing metrics.** Review major Federal efforts,[46] as well as the broader scientific literature, for science-based metrics that facilitate assessment of gray, green, and hybrid coastal infrastructure approaches, including metrics needed to develop ecological production functions, validate performance in both the short- and long-term, and examine costs. Synthesize these metrics into resources that are easily accessible and usable (e.g., a searchable online database).

(b) **Recommend metrics for major types of coastal infrastructure approaches.** For major types of gray, green, and hybrid coastal infrastructure approaches, identify a set of science-based metrics that best facilitates accurate assessment of significant changes in all relevant inputs, outputs, and outcomes. Where possible, recommended metrics should be scalable, transferable, widely accepted, easily interpretable, and require limited resources and technical expertise to apply.

(c) **Develop needed new metrics.** Develop science-based metrics to assess significant changes in inputs, outputs, and outcomes associated with various types of coastal infrastructure approaches for which existing metrics are either nonexistent or inadequate. New metrics should fulfill the criteria articulated in (b), above.

Topic 2: Ecological production functions

Advancing the integration of CGI into planning and decision making requires greater scientific understanding of the ways in which various biophysical, socioeconomic, and behavioral factors can affect CGI performance, including the delivery of protective and other ecosystem services, as well as related effects on the well-being of human populations and ecosystems. Further applied and interdisciplinary research in these areas will support development of ecological production functions – mathematical expressions that estimate the effects of changes in the structure, function, and dynamics of an ecosystem on outputs that are directly relevant and useful to decision makers – for key aspects of CGI, which can help to inform strategic deployment of CGI.

Priority research needs

(a) **Assess performance of CGI approaches under design and extreme conditions.** Examine how well various CGI approaches provide protective and other ecosystem services both under the conditions for which they have been designed, as well as in extreme conditions.

(b) **Examine effects of combining green and gray infrastructure into hybrid approaches.** Examine synergistic and detrimental effects of combining green and gray infrastructure into both tested and novel hybrid approaches, including effects on the capacity of such approaches to deliver protective and other ecosystem services, and effects on the well-being of human populations and ecosystems.

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[46] Examples include the U.S. Army Corps of Engineers Technical Report on Nature and Nature-Based Features and relevant work being conducted by the Department of the Interior's Metrics and Evaluation Group (DMEG) and the U.S. Global Climate Change Research Program (USGCRP).

(c) **Understand and assess relationships the interdependencies between and among coastal infrastructure, sea-level rise, water flows, coastal erosion, winds, and sediment movement.** Examine the effects of green, gray, and hybrid infrastructure on sea-level rise, water flows (including flows from precipitation, runoff and river systems, storm surge, tides and waves, and sea-level rise), coastal erosion, damaging winds, and sediment movement. Research should support improvement of integrated coastal and estuarine forecasting and inundation prediction. Assess how coastal erosion and sediment flow patterns affect the feasibility, costs, and performance of various infrastructure approaches.

(d) **Characterize non-linearities in ecological production functions.** Qualitatively and quantitatively describe spatial, temporal, species-related, and other sources of non-linearity – both cyclical and sustained – in ecosystem-service provision, including relevant threshold effects.

(e) **Characterize co-benefits associated with coastal infrastructure approaches.** Conduct integrated, comprehensive assessments of the major co-benefits associated with different coastal infrastructure approaches. Develop production functions that describe these co-benefits and interrelationships among them.

(f) **Characterize uncertainty and risk associated with ecological production functions.** Characterize and, where possible, quantify and/or bound uncertainties associated with ecological production functions, and the risks related to those uncertainties. This could include the use of avoided cost calculations to enhance understanding of what constitutes acceptable levels of uncertainty and related risks.

Topic 3: Ecosystem-service valuation approaches

Identifying, developing, sharing, and applying best practices for both monetary and non-monetary approaches for valuing ecosystem services and co-benefits will reduce the resources and technical expertise needed to incorporate CGI into planning and decision making; facilitate comparison of CGI approaches with alternative strategies; and improve the interpretability, transferability, and reliability of ecosystem-service valuations conducted across a broad range of spatial, temporal, ecological, and other settings. This will require consistency with other efforts to identify and describe the ecosystem services and co-benefits associated with various CGI approaches, as well as metrics for tracking and quantifying marginal changes in the provision of these services and co-benefits. To support the broad acceptance of best practices, efforts carried out in response to this recommendation should build on existing resources, such as guidance issued by the Office of Management and Budget (i.e., Circulars A-4[47] and A-94[48]). Where appropriate, efforts should also draw on expertise from Federal and non-Federal organizations, sectors, and stakeholder groups. This could include, for instance, convening of an external expert panel, similar to the blue-ribbon NOAA Panel on Contingent Valuation (Arrow et al., 1993) or the National Ecosystem Services Partnership,[49] to examine and recommend ecosystem-service valuation approaches.

Priority research needs

(a) **Improve methodologies for non-market valuation.** Improve the robustness and consistency of methodologies for stated- and revealed-preference studies, as well as other approaches for

[47] https://www.whitehouse.gov/omb/circulars_a004_a-4/.

[48] https://www.whitehouse.gov/omb/circulars_a094.

[49] https://nicholasinstitute.duke.edu/focal-areas/national-ecosystem-services-partnership.

valuing the broad range of ecosystem services and co-benefits that are not usually traded in markets (e.g., provision of habitat, aesthetic value, and cultural significance).

(b) Improve methodologies for benefit transfer. Identify CGI approaches and associated ecosystem services and co-benefits for which benefit transfer is and is not likely to serve as an appropriate valuation approach; characterize limitations and uncertainties associated with the use of benefit transfer for various CGI approaches and associated ecosystem services and co-benefits; and develop meta-regression models that leverage the increasing number and availability of valuation studies to expand the range of scenarios for which benefit transfer is likely to serve as an appropriate valuation approach, including scenarios at various spatial scales.

Topic 4: Socioeconomic and behavioral drivers

Socioeconomic and behavioral factors serve as key drivers of demand for, and supply of, ecosystem services provided by CGI. Interdisciplinary research is needed to identify and characterize these drivers. Research is also needed to understand and predict how linkages among biophysical, socioeconomic, and behavioral dynamics affect delivery of relevant ecosystem services, tradeoff decisions, and pursuit and realization of desired societal outcomes.

Priority research needs

(a) Identify key socioeconomic and behavioral drivers. Identify socioeconomic and behavioral factors that typically have significant impacts on demand for, and supply of, ecosystem services provided by CGI, as well as broader ecological, economic, and social outcomes. Examples of factors to consider include, but are not limited to, population composition, public awareness, exposure to climate impacts, sensitivity to hazards, adaptive capacity, economic impacts, and environmental justice concerns.

(b) Characterize causes and effects of changes in drivers. Conduct field studies and other applied research to investigate how drivers identified in Topic 3(a), above, evolve across time and space. This will involve research into factors, including both biophysical factors and human-driven factors, such as policy and management interventions, that may cause changes in these drivers, as well as the effects of changes on demand for, and supply of, ecosystem services provided by CGI.

(c) Model outcomes to help understand and predict linkages among drivers. Develop models to help understand and predict how linkages among key biophysical, socioeconomic, and behavioral factors affect the delivery of ecosystem services provided by CGI, as well as the ways in which such linkages influence tradeoff decisions and broader ecological, economic, and social outcomes.

Topic 5: Decision support

Successfully transitioning CGI from research and development to operation involves supplying stakeholders with the information and tools they need in order to incorporate CGI into their standard decision-making processes. This includes information suggesting that CGI projects are viable, cost-competitive, and low-risk alternatives to conventional approaches, ways to visualize and interpret changes in ecosystems and the delivery of associated ecosystem services, and tools that aid in strategic CGI deployment, including comparison of CGI approaches with alternative strategies. Additional effort is needed to develop these resources, ensure that they are made accessible and useful for decision makers, and establish mechanisms through which these resources can be exchanged and continuously updated with new knowledge and lessons learned from ongoing and future investigation and use of CGI.

Priority research needs

(a) Identify appropriate CGI performance and cost objectives. Identify appropriate performance and cost objectives for different types of CGI approaches, taking into account life-cycle costs associated with both conventional approaches and CGI, as well as unique values associated with CGI (e.g., through provision of co-benefits or potential natural adaptability to environmental changes).

(b) Develop frameworks for demonstrating and validating objectives. Develop demonstration and validation frameworks for determining whether a given CGI project meets performance and cost objectives under various plausible short- and long-term scenarios, including scenarios of future climate change. Frameworks should include explicit designs for testing CGI approaches and their performance under current conditions, and may include the use of models or other tools that can simulate testing of CGI approaches under possible future conditions. Frameworks should also identify data and data-collection mechanisms needed to support such performance testing, as well as the development of appropriate life-cycle cost models for CGI.

(c) Create tools to inform CGI site selection. Create tools to help identify and visualize sites amenable to, and likely to benefit from, CGI projects by integrating data and other information on relevant physical (e.g., bathymetry, geomorphology, fetch, elevation, weather, and climate) and socioeconomic (e.g., population density, property values, critical facilities, and available emergency services) aspects of the Nation's coasts.

(d) Create tools to help reconcile multiple planning and decision-making considerations. Create tools that integrate relevant data and other information in order to facilitate comparison of CGI and alternative strategies (e.g., gray infrastructure, structural elevation, and inland movement) in the context of other key considerations such as competing management objectives, socioeconomic considerations, and policy directives.

(e) Identify and promote best practices for management of CGI data. Identify and promote consistent and, where appropriate, standardized practices for management of data related to ecosystem-service assessment and to the results of performance tests and cost models of CGI approaches, in order to support data interoperability. This includes practices for collection, formatting, organization, dissemination, and long-term maintenance of relevant data.

(f) Facilitate sharing of information resources. Improve and, where necessary, establish mechanisms through which public, private, academic, non-profit, and other sectors can share information and tools that support the broad integration of CGI into decision making. Such mechanisms could include an interagency repository to facilitate exchange and visualization of relevant data; a library of ecological production functions for CGI; a widely accessible database of designs, engineering specifications, and performance test results CGI pilot and demonstration projects; a centralized online portal for decision-support tools related to CGI and ecosystem services, etc. These mechanisms should build on existing resources, such as the Climate Resilience Toolkit (Box 3). Effort should also be made to develop approaches that encourage ongoing and proactive use of these mechanisms to inform planning and decision making.

Box 3. Building on existing resources: the Climate Resilience Toolkit

The U.S. Climate Resilience Toolkit (CRT), an online Federal resource launched in November 2014, provides scientific tools, information, and expertise to help people manage their climate-related risks and opportunities and improve their resilience to extreme events. The CRT includes freely available case studies, maps and other visualizations, training courses, and other tools to assist users in understanding climate problems and discover solutions that help communities mitigate and adapt to the effects of climate change, while simultaneously boosting local economies, creating new jobs, and improving ecosystem health.

The CRT includes resources that can inform efforts to prepare for and respond to climate-related coastal hazards. One example is the Federal Emergency Management Agency (FEMA)'s Risk Mapping, Assessment, and Planning (Risk MAP) program. Through collaboration with state, tribal, and local entities, Risk MAP provides data and support tools to help citizens and communities reduce flood risk and damage. Such resources will become increasingly important for coastal areas, as climate change continues to drive rising sea levels and associated coastal flood risks.

6. Conclusion

Ecosystem-Service Assessment: Research Needs for Coastal Green Infrastructure recommends areas for prioritized Federal research to support the integration of coastal green infrastructure and ecosystem-service considerations into risk-reduction efforts, climate-resilience planning, and decision making. Moving forward, Federal agencies should, where possible, ensure that efforts carried out in response to these recommendations align with work and guidance on green infrastructure and ecosystem services more broadly, including efforts at both the Federal and non-Federal levels.

7. Glossary

Benefit transfer: The process of applying the monetary values estimated in existing empirical studies to assess the value of a quantified effect in a different study.

Coastal green infrastructure: See "green infrastructure," below. Coastal green infrastructure refers to green infrastructure based on the characteristics and needs of coastal regions.

Ecological production functions: Mathematical expressions that estimate the effects of changes in the structure, function, and dynamics of an ecosystem on outputs that are directly relevant and useful to decision makers.

Ecosystem: The dynamic complex of plant, animal, and microorganism communities and the non-living environment interacting as a system.

Ecosystem services: The direct or indirect contribution, including economic, environmental, and social effects, which ecosystems make to the environment and human populations.

Ecosystem-service assessment: An integrated and systematic approach to characterizing all significant ecosystem services in an area of interest, including, as appropriate, qualitative, quantitative, and/or monetized evaluation of these services.

Ecosystem-service valuation: The process of measuring values associated with a change in the services that an ecosystem provides.

Gray infrastructure: Components of a system that are neither naturally occurring nor designed to mimic natural systems or processes (e.g., seawalls, levees, bulkheads, pipes and sewers, etc.). Also known as "built" or "hard" infrastructure.

Green infrastructure: The integration of natural systems and processes, or engineered systems that mimic natural systems and processes (i.e., nature-based features), into investments in resilient infrastructure. Green infrastructure includes natural and/or restored features (e.g., wetlands or sand dune ecosystems), that incorporate the natural processes (e.g., flood protection, water filtration) that are recognized as integral to community, economic, and environmental resilience.

Hybrid infrastructure: Infrastructure that incorporates both engineered and natural elements.

Natural features: Features that are created and evolve over time through the actions of physical, biological, geologic, and chemical processes operating in nature.

Outcome: The result or consequence of an action. Outcomes are of direct importance to beneficiaries and the public generally, and may be associated with a change in one or more outputs.

Output: A good or service produced by an entity.

Resilience: The ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions.

Vulnerability: The degree to which a system's attributes of concern are susceptible to, and unable to cope with, the adverse effects of hazards over a period of time or temporal reference.

8. References

Abt Associates, 2014: Estimating the Change in Ecosystem Services Values from Coastal Restoration. Available at http://www.abtassociates.com/AbtAssociates/files/9d/9d17a4b8-cdd7-4e69-bdf6-96404b3b591b.pdf.

Arkema, K.K., G. Guannel, G. Verutes, S.A. Wood, A. Guerry, M. Ruckelshaus, P. Kareiva, M. Lacayo, J.M. Silver, 2013: Coastal habitats shield people and property from sea-level rise and storms. *Nat. Clim. Chang.*, 3, 913-918.

Arrow, K., R. Solow, P.R. Portney, E.E. Leamer, R. Radner, H. Shuman., 1993: Report of the NOAA Panel on Contingent Valuation. Federal Register, 58, 4601-4614.

Axley, J., 2013: Green Infrastructure to Enhance Resistance to Natural Hazards. URS FEM TARC 12-J-0009: White Paper. Yale University.

Barbier, E.B., B.S. Enchelmeyer, 2014: Valuing the storm surge protection service of US Gulf Coast wetlands. *J. Environm. Econ. Pol.*, 3(2), 167-185.

Barbier, E.B., S.D. Hacker, C. Kennedy, E. Koch, A.C. Stier, B.R. Silliman, 2011: The value of estuarine and coastal ecosystem services. *Ecol. Monogr.*, 81(2), 169-193.

Barnett, J., S. Graham, C. Mortreux, R. Fincher, E. Waters, A. Hurlimann, 2014: A local coastal adaptation pathway. *Nat. Clim. Chang.*, 4, 1103-1108.

Batker, D., I. de la Torre, R. Costanza, P. Swedeen, J. Day, R. Boumans, K. Bagstad, 2010: Wetlands, Hurricanes and the Economy: The Value of Restoring the Mississippi River Delta. Earth Economics, Tacoma, WA. Available at http://www.eartheconomics.org/FileLibrary/file/Reports/Louisiana/Earth_Economics_Report_on_the_Mississippi_River_Delta_compressed.pdf.

Bernd-Cohen, T., M. Gordon, 1998: State Coastal Management Effectiveness in Protecting Beaches, Dunes, Bluffs, Rocky Shores: A National Overview. Part of the Sea Grant National CZM Effectiveness Study for the Office of Ocean and Coastal Resource Management National Ocean Service. Available at http://www.ikzm-oder.de/pl/download.php?fileid=272.

Bilkovic, D., M. Mitchell, 2013: Ecological tradeoffs of stabilized salt marshes as a shoreline protection strategy: Effects of artificial structures on macrobenthic assemblages. *Ecol. Eng.*, 61, 469-481.

Bockstael, N.E., K.E. McConnell, 2007: Environmental and Resource Valuation with Revealed Preferences: A Theoretical Guide to Empirical Models, Dordrecht, The Netherlands: Springer.

Bouma, T.J., J. van Belzen, T. Balke, Z. Zhu, L. Airoldi, A.J. Blight, A.J. Davies, C. Galvan, S.J. Hawkins, S.P.G. Hoggart, J.L. Lara, I.J. Losada, M. Maza, B. Ondiviela, M.W. Skov, E.M. Strain, R.C. Thompson, S. Yang, B. Zanuttigh, L. Zhang, P.M.J. Herman, 2014: Identifying knowledge gaps hampering application of intertidal habitats in coastal protection: Opportunities & steps to take. *Coast. Eng.*, 87, 147-157.

Bowles, S., 2008: Policies designed for self-interested citizens may undermine “the moral sentiments”: evidence from economic experiments. *Science*, 320(5883), 1605-1609.

Boyd, J., S. Banzhaf, 2007: What are ecosystem services? The need for standardized environmental accounting units. *Ecol. Econ.*, 63, 616-626.

Bridges, T., R. Henn, S. Komlos, D. Scerno, T. Wamsley, K. White, 2013: Coastal Reisk Reduction and Resilience: Using the Full Array of Measures. U.S. Army Corps of Civil Works, CWTS 2013-3. Available at http://www.corpsclimate.us/docs/USACE_Coastal_Risk_Reduction_final_CWTS_2013-3.pdf.

Bridges, T.S., P.W. Wagner, K.A. Burks-Copes, M.E. Bates, Z.A. Collier, C.J. Fischenrich, J.Z. Gailani, L.D. Leuck, C.D. Piercy, J.D. Rosati, E.J. Russo, D.J. Shafer, B.C.Suedel, E.A. Vuxton, T.V. Wamsley, 2015: Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience. U.S. Army Corps of Civil Works, ERDC SR-15-1. Available at http://www.nad.usace.army.mil/Portals/40/docs/NACCS/NNBF FINAL.pdf.

Burkett, V.R., M.A. Davidson, 2012: Coastal Impacts, Adaptation, and Vulnerability: A Technical Input to the 2012 National Climate Assessment. Cooperative Report to the 2013 National Climate Assessment, 150 pp. Available at http://cakex.org/virtual-library/coastal-impacts-adaptation-and-vulnerabilities-technical-input-2013-national-climate.

Cahoon, D.R., D. J. Reed, A. S. Kolker, M. M. Brinson, J. C. Stevenson, S. Riggs, R. Christian, E. Reyes, C. Voss, and D. Kunz (2009), Coastal wetland sustainability, in Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region, 57-72. United States Climate Change Science Program, Washington, D. C.

Cavanaugh, K.C., J.R. Kellner, A.J. Forde, D.S. Gruner, J.D. Parker, W. Rodriguez, I.C. Feller, 2014: Poleward expansion of mangroves is a threshold response to decreased frequency of extreme cold events. *P. Natl. Acad. Sci. USA*, 111, 723-727.

Champ, P.A., K.J. Boyle, T.C. Brown (eds), 2003: A Primer on Nonmarket Valuation, Dordrecht, The Netherlands: Kluwer Academic Publishers.

Christie, M., I. Fazey, R. Cooper, T. Hyde, A. Deri, L. Hughes, L., G. Bush, L. Brander, A. Nahman, W. de Lange, B. Reyers, 2008: An evaluation of economic and non-economic techniques for assessing the importance of biodiversity to people in developing countries. *Ecol. Econ.*, 83, 67-78.

City of New York Department of City Planning, 2013: Urban Waterfront Adaptive Strategies. Available at http://www.nyc.gov/html/dcp/pdf/sustainable_communities/urban_waterfront_print.pdf.

Coastal Green Infrastructure Research Plan for New York City, 2014: Prepared for the Hudson River Estuary Program, New York State Department of Environmental Conservation, with support from the New York State Environmental Protection Fund, in cooperation with the New England Interstate Water Pollution Control Commission. Available at http://www.dec.ny.gov/docs/remediation_hudson_pdf/cginyc.pdf.

Coasts at Risk: An Assessment of Coastal Risks and the Role of Environmental Solutions, 2014: Beck, M.W. (ed.), A joint publication of United Nations University – Institute for Environment and Human Security (UNU-EHS), The Nature Conservancy (TNC) and the Coastal Resources Center (CRC) at the University of Rhode Island Graduate School of Oceanography. Available at http://www.crc.uri.edu/download/SUC09_CoastsatRisk.pdf.

Costanza, R., O. Perez-Maqueo, M.L. Martinez, P. Sutton, S.J. Anderson, K. Mulder, K, 2008: The value of coastal wetlands for hurricane protection. *Ambio*, 37(4), 241-248.

Day, D., D. Boesch, E. Clairain, G. Kemp, S. Laska, W. Mitsch, 2007: Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita. *Science*, 315(5819):1679-84.

Edwards, P.E.T., Sutton-Grier A.E. & Coyle, G. 2013: Investing in Nature: Restoring Coastal Habitat Blue Infrastructure and Green Job Creation. *Marine Policy*. 38:65-71

Environmental Protection Agency (EPA), 1999: Section 7.3: Benefits Transfer. In Economic Analysis Resource Document. Innovative Strategies and Economics Group, Office of Air Quality Planning & Standards. Available at http://www.epa.gov/ttnecas1/econdata/Rmanual2/7.3.html.

Environmental Protection Agency (EPA), 2009: Valuing the Protection of Ecological Systems and Services. EPA-SAB-09-012. Available at http://yosemite.epa.gov/sab%5CSABPRODUCT.NSF/F3DB1F5C6EF90EE1852575C500589157/$File/EPA-SAB-09-012-unsigned.pdf.

Environmental Protection Agency (EPA), 2010: Guidelines for Preparing Economic Analyses. National Center for Environmental Economics, Office of Policy, U.S. Environmental Protection Agency. Available at http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0568-50.pdf/$file/EE-0568-50.pdf.

Environmental Protection Agency (EPA), 2013: The Importance of Operation and Maintenance for the Long-Term Success of Green Infrastructure. Office of Water. Available at http://water.epa.gov/grants_funding/cwsrf/upload/Green-Infrastructure-OM-Report.pdf.

Environmental Protection Agency (EPA), 2014: Ecosystem service valuation. Available at http://www.epa.gov/sustainability/analytics/eco-service-valuation.htm.

Eastern Research Group, 2014: A Policy Analysis of the Use of Ecosystem Services Values in State and Local Decision-Making: Potential Policy Questions and Gaps Analysis. Prepared for the NOAA Coastal Services Center. Available at http://coast.noaa.gov/digitalcoast/sites/default/files/files/publications/16012015/ESVPolicyAnalysis.pdf.

Executive Order 13653, 3 C.F.R., 2013: Preparing the United States for the Impacts of Climate Change.

Ferrario, F., M.W. Beck, C.D. Storlazzi, F. Micheli, C.C. Shepard, L. Airoldi, 2014: The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. Nat. Comm., 5(3794), 1-9.

Fisher, B.R., K. Turner, P. Morling, 2009: Defining and classifying ecosystem services for decision making. Ecol. Econ., 68(3), 643-653.

Freed, A., E. Percifull, C. Kaiser, J. Goldstick, M. Wilson, E. Maxwell, 2013: Integrating Natural Infrastructure into Urban Coastal Resilience: Howard Beach, Queens. The Nature Conservancy, New York, NY. Available at http://www.nature.org/media/newyork/howard-beach-report-12-23-2013.pdf.

Freeman, A.M., 2003: The Measurement of Environmental and Resource Values: Theory and Methods, 2nd edition, Washington: Resources for the Future.

Gartner, T., J. Mulligan, R. Schmidt, J. Gunn (eds), 2013: Natural Infrastructure: Investing in Forested Landscapes for Source Water Protection in the United States. World Resources Institute. Available at http://www.wri.org/sites/default/files/wri13_report_4c_naturalinfrastructure_v2.pdf.

Global Insight, Inc., 2014: U.S. Metro Economies: Income and Wage Gaps Across the US. Prepared for The United States Conference of Mayors and The Council on Metro Economies and the New American City.

Government Printing Office, 2006: Hurricane Katrina: Why Did the Levees Fail. 109th Congress, testimony of Peter Nicholson, PhD, P.E., 14.

Hanley, N., R.E. Wright, V. Adamowicz, 1998: Using Choice Experiments to Value the Environment: Design Issues, Current Experience, and Future Prospects. Environ. Resour. Econ., 11(3-4): 413-428.

Herriges, J.A., C.L. Kling, 1999: Valuing Recreation and the Environment: Revealed Preference Methods in Theory and Practice, Northampton, MA: Edward Elgar.

Howard Beach Planning Committee, 2014: Howard Beach Program Information Meeting Committee Meeting #7. Available at http://stormrecovery.ny.gov/sites/default/files/crp/community/documents/012714_howardbeach_pc7_presentation.pdf.

Hurricane Sandy Rebuilding Task Force (HSRTF), 2013: Hurricane Sandy Rebuilding Strategy: Stronger Communities, A Resilient Region. Available at http://portal.hud.gov/hudportal/documents/huddoc?id=hsrebuildingstrategy.pdf.

Johnston, R., R. Rosenberger, 2010: Methods, trends, and controversies in contemporary benefit transfer. J. Econ. Surv., 24(3), 479-510.

Kelemen, E., M. García-Llorente, G. Pataki, B. Martín-López, E. Gómez-Baggethun, 2014: Non-Monetary Techniques for the Valuation of Ecosystem Services. In Potschin, M., K. Jax, (eds.), OpenNESS Reference Book. EC FP7 Grant Agreement no. 308428.

Kling, C.L., D.J. Phaneuf, J. Zhao, 2012: From Exxon to BP: Has Some Number Become Better than No Number? J. Econ. Perspect., 26(4): 3-26.

Koch, E.W., E.B. Barbier, B.R. Silliman, D.J. Reed, G.M. Perillo, S.D. Hacker, E.F. Granek, J.H. Primavera, N. Muthiga, S. Polasky, B.S. Halpern, C.J. Kennedy, C.V. Kappel, E. Wolanski, 2009: Non-linearity in ecosystem services: temporal and spatial variability in coastal protection. Front. Ecol., 7(1), 29-37.

Kroeger, T., 2012: Dollars and Sense: Economic Benefits and Impacts from Two Oyster Reef Restoration Projects in the Northern Gulf of Mexico. The Nature Conservancy, Arlington, VA, 110 pp. http://www.nature.org/ourinitiatives/regions/northamerica/oyster-restoration-study-kroeger.pdf.

Langridge, S.M., E.H. Hartge, R. Clark, K. Arkema, G.M. Verutes, E.E. Prahler, S. Stoner-Duncan, D.L. Revell, M.R. Caldwell, A.D. Guerry, M. Ruckelshaus, A. Abeles, C. Coburn, K. O'Connor, 2014: Key lessons for incorporating natural infrastructure into regional climate adaptation planning. Ocean Coast. Manage., 95, 189-197.

Massel, S.R., K. Furukawa, R.M. Brinkman, 1999: Surface wave propagation in mangrove forests. Fluid Dyn. Res., 24, 219-249.

Millennium Ecosystem Assessment (MEA), 2003: Ecosystems and Human Well-Being: A Framework for Assessment. Island Press. Available at http://www.unep.org/maweb/en/Framework.aspx.

Mitchell, R.C., R.T. Carson, 1989: Using Surveys to Value Public Goods: The Contingent Valuation Method, Washington, D.C.: Resources for the Future.

Möller, I., M. Kudella, F. Rupprecht, T. Spencer, M. Paul, B.K. van Wesenbeeck, G. Wolters, K. Jensen, T.J. Bouma, M. Miranda-Lange, S. Schimmels, 2014: Wave attenuation over coastal salt marshes under storm surge conditions. Nat. Geo., 7, 727-731.

Moser, S.C., M.A. Davidson, P. Kirshen, P. Mulvaney, J.F. Murley, J.E. Neumann, L. Petes, D. Reed, 2014: Chapter 25: Coastal Zone Development and Ecosystems. In J.M. Melillo, T.C. Richmond, G.W. Yohe, (eds.), Climate Change Impacts in the United States: The Third National Climate Assessment, 579-618.

Moser, S.C., S.J. Williams, D.F. Boesch, 2012: Wicked challenges at Land's End: Managing coastal vulnerability under climate change. Annu. Rev. Env. Ecosyt., 37, 51-78.

Murray, E.O., G.F. Mendoza, L. Wainger, H. Griscom, J. Cushing, 2014 (in press): Ecosystem Goods and Services Models and Tools —A Synthesis Report of information found in the EGS Models and Tools Catalog. U.S. Army Engineer Research and Development Center, Vicksburg, MS.

National Climatic Data Center, 2013: Billion-Dollar Weather/Climate Disasters: Overview. Available at http://www.ncdc.noaa.gov/billions/.

National Ecosystem Services Partnership, 2014: Federal Resource Management and Ecosystem Services Guidebook. National Ecosystem Services Partnership, Duke University, Durham, NC. Available at https://nespguidebook.com.

National Oceanic and Atmospheric Administration (NOAA), 2012a: Protecting the Public Interest through the National Coastal Zone Management Program: How Coastal States and Territories Use No-Build Areas along Ocean and Great Lake Shorefronts. Office of Ocean and Coastal Resource Management. Available at http://coastalmanagement.noaa.gov/ resources/publications.html.

National Oceanic and Atmospheric Administration (NOAA), 2012b: Spatial Trends in Coastal Socioeconomics Demographics Trends Database: 1970-2010. Available at http://coastalsocioeconomics.noaa.gov/.

National Oceanic and Atmospheric Administration (NOAA), 2013: Service Assessment: Hurricane/Post-Tropical Cyclone Sandy, October 22-29, 2012. Silver Spring, MD: National Weather Service. Available at http://www.nws.noaa.gov/os/assessments/pdfs/Sandy13.pdf.

National Oceanic and Atmospheric Administration (NOAA), 2014: Economic Assessment of Green Infrastructure Strategies for Climate Change Adaptation: Pilot Studies in The Great Lakes Region. Written by Eastern Research Group, Inc. for the NOAA Coastal Services Center. Available at https://coast.noaa.gov/digitalcoast/sites/default/files/files/publications/04062014/GLPilots_Final_5-5-14v2.pdf.

National Research Council (NRC), 2005: Valuing Ecosystem Services: Toward Better Environmental Decision-Making. New York: The National Academies Press.

National Research Council (NRC), 2014: Reducing Coastal Risks on the East and Gulf Coasts. Committee on U.S. Army Corps of Engineers Water Resources Science, Engineering, and Planning: Coastal Risk Reduction; Water Science and Technology Board; Ocean Studies Board; Division on Earth and Life Studies; National Research Council. 130 pp. Available at http://www.nap.edu/catalog/18811/reducing-coastal-risk-on-the-east-and-gulf-coasts.

Ninan, K.N., 2014: Valuing Ecosystem Services: Methodological Issues and Case Studies. Edward Elgar Publishing. 464 pp.

Office of Management and Budget (OMB), 1992. Circular No. A-94 Revised: Guidelines and Discount rates for Benefit-Cost Analysis of Federal Programs. Available at https://www.whitehouse.gov/omb/circulars_a094.

Office of Management and Budget (OMB), 2003. Circular No. A-4: Regulatory Analysis. Available at https://www.whitehouse.gov/omb/circulars_a004_a-4/.

Palmer, C., 2013: Bay Area environmental group proposes hybrid levees for bay. San Jose Mecury News. Available at http://www.mercurynews.com/science/ci_22651840/bay-area-environmental-group-proposes-hybrid-levees-bay?source=email.

Perry, C.T., G.N. Murphy, P.S. Kench, S.G. Smithers, E.N. Edinger, R.S. Steneck, P.J. Mumby, 2013: Caribbean-wide decline in carbonate production threatens coral reef growth. Nat. Comm., 4(4102).

Priority Agenda: Enhancing the Cliamte Resilience of America's Natural Resources, 2014: Prepared by the Climate and Natural Resources Working Group of the Council on Climate Preparedness and Resilience. Available at https://www.whitehouse.gov/sites/default/files/docs/enhancing_climate_resilience_of_americas_natural_resources.pdf.

Ribaudo, M., L. Hansen, D. Hellerstein, C. Greene, 2008: The Use of Markets to Increase Private Investment in Environmental Stewardship. ERR-64, 77 pp.

Richardson, L., J. Loomis, T. Kroeger, F. Casey, 2014. The role of benefit transfer in ecosystem service valuation Ecol. Econ. Available at http://dx.doi.org/10.1016/j.ecolecon.2014.02.018.

Shephard, C.C., C.M. Crain, M.W. Beck, 2011: The protective role of coastal marshes: a systematic review and meta-analysis. PLoS ONE, 6(11).

Sustaining Environmental Capital: Protecting Society and the Economy, 2011: Prepared by the President's Council of Advisors on Science and Technology. Available at https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_sustaining_environmental_capital_report.pdf.

Sutton-Grier, A., H. Bamford, K. Wowk, 2015: Future of our coasts: The potential for natural and hybrid infrastructure to protect our coastal communities and economies. Environ. Sci. Policy, 51, 137-148.

The Economics of Ecosystems and Biodiversity (TEEB), 2010: Ecological and Economic Foundations. Kumar, P. (ed.), Earthscan, London and Washington. Available at http://www.teebweb.org/publication/the-economics-of-ecosystems-and-biodiversity-teeb-ecological-and-economic-foundations/.

UNEP-WCMC, 2006: In the Front Line: Shoreline Protection and other Ecosystem Services from Mangroves. UNEP World Conservation Monitoring Centre, Cambridge, UK, 33 pp. Available at http://www.unep.org/pdf/infrontline_06.pdf.

U.S. Army Corps of Engineers (USACE), 2004: Low Cost Shore Protection: A Guide for Engineers and Contractors. Lighning Source Incorporated, 180 pp.

U.S. Army Corps of Engineers (USACE), 2009: Louisiana Coastal Protection and Restoration Final Technical Report. New Orleans District, Mississippi Valley Division. Available at http://www.mvn.usace.army.mil/Portals/56/docs/environmental/LaCPR/LACPRFinalTechnicalReportJune2009.pdf.

U.S. Army Corps of Engineers (USACE), 2013: Coastal Risk Reduction and Resilience. CWTS 2013-3, Directorate of Civil Works, Washington, DC.

U.S. Army Corps of Engineers (USACE), 2014. Economic Guidance Memorandum, 15-01, Federal Interest Rates for Corps of Engineers Projects for Fiscal Year 2015. Available at http://planning.usace.army.mil/toolbox/library/EGMs/EGM15-01.pdf.

U.S. Army Corps of Engineers (USACE), 2015: Ecological Production Functions. Environmental Benefits Analysis (EBA) program. Available at http://cw-environment.usace.army.mil/eba/framework.cfm?Option=Functions.

U.S. Fish & Wildlife Service (USFWS), 2010: Strategic Plan, The Coastal Program: Stewardship of Fish and Wildlife Through Voluntary Conservation. Available at http://www.fws.gov/coastal/docs/785.pdf.

U.S. Fish & Wildlife Service (USFWS), 2014: Coastal Program. Available at http://www.fws.gov/coastal/.

U.S. Global Change Research Program (USGCRP), 2012: The National Global Change Research Plan 2012-2021. See, for example, "Box 15. Sea Level Rise and Coastal Vulnerability," p. 35. Available at http://www.globalchange.gov/browse/reports/national-global-change-research-plan-2012–2021-strategic-plan-us-global-change.

Walker, B., D. Salt, 2006: Resilience Thinking: Sustaining Ecosystems and People in a Changing World. Island Press.

White House Council on Environmental Quality, 2013: Principles and Requirements for Federal Investments in Water Resources. Available at https://www.whitehouse.gov/sites/default/files/final_principles_and_requirements_march_2013.pdf.

Woods and Poole Economics, Inc., 2011: Complete Economic and Demographic Dataset. Available at http://www.woodsandpoole.com/main.php?cat=country. Data processed by NOAA to determine coastal county summary totals and absolute and percent change.