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PERSPECTIVES

A Blueprint to Greener Shorelines: Advancing the Effectiveness, Sustainability, and Widespread Adoption of Coastal Nature-Based Solutions Through Transdisciplinary Research

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Abstract
Coastal nature-based solutions (NbS) have emerged as powerful tools to enhance sustainable development and ecological restoration goals. As a rapidly growing field spanning across social, political, ecological, economic, and engineering disciplines, it is critical that researchers working in coastal NbS regularly attempt to identify emerging focal areas for scientific inquiry. Following the 27th Biennial meeting of the Coastal and Estuarine Research Federation, we provide a transdisciplinary perspective (including biologists, engineers, oceanographers, geoscientists, economists, and facilitators of workforce training programs) of pertinent research questions that, if answered, will advance the effectiveness, sustainability, and widespread adoption of coastal NbS. These suggestions for future research highlight the necessity for diverse expertise and perspectives at every stage in planning, design, implementation, and monitoring coastal NbS.

Keywords Natural and nature-based infrastructure · Ecological engineering · Ecosystem service · Living shorelines

Introduction

In 2019, the United Nations (UN) General Assembly passed Resolution 73/284, declaring 2021–2030 the Decade on Ecosystem Restoration and building a global movement to reverse the degradation of ecosystems (United Nations Environment Agency, 2019). Nature-based solutions (NbS), actions that leverage nature to safeguard people, infrastructure, and biodiversity, have the potential to substantially contribute to achieving UN Sustainable Development Goals pertaining to climate change, biodiversity, and human well-being (IUCN, 2020; Seddon et al., 2020a). In the coastal landscape, there is growing interest in the use of NbS to enhance coastal resilience to hazards (Sutton-Grier et al., 2015; Moraes et al., 2022; O'Leary et al., 2023; Paxton et al., 2024). This subset of NbS, hereto referred to as "coastal NbS", encompasses a diverse array of practices that restore or create coastal ecosystems with or without engineered structures (Sutton-Grier et al., 2015). Coastal NbS are specifically designed to provide coastal protection services and are considered "ecologically friendly" alternatives to traditional shoreline armoring as they also provide co-benefits such as biodiversity. As living systems, coastal NbS are idealized as an anticipatory response to adapt to changing environmental conditions, for example, by accreting elevation or migrating landward in response to sea level rise (Doelle & Puthucherril, 2023).

Recent publications have identified important factors limiting the use of NbS in coastal and estuarine regions, including societal attitudes within coastal communities, ecological knowledge gaps, lack of monitoring data, and climate uncertainty (Arkema et al., 2017; Saunders et al., 2020; Smith et al., 2020; Lebbe et al., 2021; Cohn et al., 2021; Favero & Hinkel, 2024; Huynh et al., 2024). Solutions to these limitations span scientific, socio-political, and economic domains. For example, van Rees et al. (2023) highlighted the need for a global dialogue that included under-represented groups to mainstream NbS in coastal infrastructure design

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and development. van der Meulen et al. (2023) identified the need for cost–benefit analyses. O'Leary et al. (2023) emphasized the need to establish guidance on effective designs within broader spatial scales and increase scientific communication to stakeholders. Palinkas et al. (2022) identified the need to integrate robust monitoring of projects. Saleh and Weinstein (2016) emphasized the need to evaluate site-specific conditions that may influence coastal NbS effectiveness. Further, multiple studies have identified a need to better understand coastal NbS resilience to storm events (Saleh & Weinstein, 2016; Spiering et al., 2021). Despite the significant contributions of these and many other studies to our knowledge base, there are still knowledge gaps. Now, at a mid-point in the UN's Decade on Ecosystem Restoration, we offer our suggested focal areas for research to increase the effectiveness (defined as the ability for NbS to meet ecosystem service provision goals), sustainability (defined as longevity in functionality and adaptability to changing environmental conditions), and widespread adoption (defined as willingness and preparedness to adopt NbS across broad geographic regions and socioeconomic settings) of coastal NbS (Fig. 1).

Advancing the rapidly developing field of coastal NbS requires perspectives from multiple fields, including but not limited to biology, geology, hydrology, engineering, policy, outreach and education, social science, environmental economics, and industry. The session "Nature-based solutions for coastal ecosystems: successes, failures, and lessons learned" at the 27th Biennial meeting of the Coastal and Estuarine Research Federation brought together researchers and practitioners working on coastal NbS from the U.S., Australia, and Southeast Asia. As a collaborative team, we generated a list of scientific questions that, if answered, would advance the capacity for coastal NbS to provide structural, ecological, and societal benefits now and in the future. Questions were grouped by common themes and then prioritized within each group. We emphasize research themes that aim to improve the achievement of project outcomes (effective), increase project adaptability over time (sustainable), and/or promote wider adoption of coastal NbS (widespread),

Fig. 1 Framework illustrating recommended areas of research needed to improve the effectiveness, sustainability, and widespread use of nature-based solutions (NbS) in coastal settings. Thicker blue arrows emphasize the idealized chain of events: coastal NbS should be proven effective and sustainable before becoming widespread. The thin black arrows show the iterative and reciprocal nature of these feedbacks in practice. While achieving these three goals concurrently may be possible, each may be achieved in isolation. For example, NbS that show immediate effectiveness may gain widespread adoption before evidence of their sustainability emerges. If a NbS is shown to be sustainable, it may or may not provide desired coastal protection benefits. In certain cases, widespread implementation of coastal NbS projects may increase collective effectiveness and sustainability. Images were created using Meta AI with Llama 3. Image of Earth modified from open access image database 123RF

in isolation or in combination (Fig. 1). Finally, we demonstrate our proposed approach to developing research in each of and across these themes using specific case study examples from diverse coastal NbS from around the world (Supplementary Figs. 1–3).

Research for Effective Coastal NbS

Unlike traditional shoreline armoring approaches, coastal NbS aim to provide coastal protection as well as ecological, economic, and social co-benefits (hereby referred to as "effectiveness"). There is a growing body of evidence that supports the capacity for coastal NbS to provide these benefits (Isdell et al., 2021; Jordan & Fröhle, 2022; Morris et al., 2018; Schoonees et al., 2019; Smith et al., 2020), but most evidence stems from studies conducted at local spatial and short temporal scales (Paxton et al., 2024). Further, this evidence is highly variable and often related to site-specific dynamics (e.g., hydrogeomorphic setting, connectivity) (Chambers et al., 2021; Morris et al., 2022; Pittman et al., 2022; Smith et al., 2020; Young et al., 2023). Several studies have identified a lack of design guidance and uncertainties in benefits as a barrier to implementation (Bilkovic et al., 2016; Gijsman et al., 2021; Morris et al., 2024). Here, we highlight several overarching research needs (roman numerals) and key questions (bullet points) that, if answered, would inform coastal NbS designs and reduce uncertainties regarding ecosystem services (Fig. 1).

i. Quantify the Effects of Project Design and Materials on Achievement of Ecosystem Service Provision Goals

Coastal NbS cover a broad range of solutions that include the creation of habitats, the enhancement of existing habitats, and the ecological enhancement of existing coastal structures (Pontee, 2022). Hence, a diverse array of designs and materials can be configured to address coastal hazards and provide co-benefits (Sakr & Altieri, 2025). Additionally, site-specific factors (e.g., wind waves, shoreline type, upland and shoreline slope, shoreline width, water depth, erosion rate, and sunlight exposure) often influence NbS designs and materials. However, the efficacy of coastal NbS with similar designs and materials may vary across diverse coastal settings (Marino et al., 2025). Thus, research has focused on understanding how designs and materials affect the provision of ecosystem services (Morris et al., 2022; Bianciardi et al., 2023). For example, laboratory and field studies have increased our understanding of how size, shape, and orientation of both biogenic habitats and engineered coastal structures influence wave attenuation (e.g., Barry et al., 2025; Dunlop, 2016; Morris et al., 2021; Phan et al., 2019). Longitudinal field studies have been important in quantifying how a variety of coastal NbS impact ecosystem structure and function over time, such as rates of vegetation growth (Davis et al., 2022; Payne et al., 2021; Raposa et al., 2023), carbon dynamics (Puchkoff & Lawrence, 2022), and accretion rates (Fitri et al., 2015; Mai Van et al., 2021). More recently, computer models have been developed to predict ecosystem development of coastal NbS (Familkhalili et al., 2023; Morris & Staver, 2024; Staver et al., 2024) and identify designs and materials that maximize ecosystem services (Huff et al., 2022; Wang et al., 2023; Zhu et al., 2023). While these previous studies have advanced our understanding of best practices for designing coastal NbS, additional studies are needed to optimize designs and materials for specific environmental conditions. We encourage researchers to continue exploring innovative designs (e.g., material placement and configuration), refine and expand the use of computer models, and rigorously test novel designs and materials (e.g., non-plastic, low-cost, biodegradable materials, and concrete alternatives with a lower carbon footprint). Importantly, research approaches are needed in both controlled settings and in the field where the influence of complex site heterogeneity can be evaluated.

Additionally, we encourage continued refinement of metrics to determine those that are most informative for assessing coastal NbS effectiveness. Physical metrics such as wave height reduction and shoreline change rate are commonly employed, as these are directly correlated with a project's capacity to provide shoreline protection. But additional research is needed to understand variability in the relationships between these physical metrics and project outcomes. Metrics selected to assess whether the project is providing desired ecological co-benefits are more nebulous. Often, selected metrics prioritize a few focal species (e.g., habitat-building plant or mollusk species) but overlook non-habitat-building taxa (e.g., birds, fish, and mammals) or taxa that are challenging to sample (e.g., microbial communities). Additionally, assessments of metric quantification approaches (e.g., remote sensing vs. field-collections) are needed to determine best practices for measuring a project's effectiveness. For example, what methods and spatiotemporal resolutions are adequate for characterizing complex biological and physical dynamics at a site to optimize accuracy and time-/cost-effectiveness?

Key Questions

- Which placement configurations or shapes of coastal NbS structures accelerate the establishment of habitat-forming species, and how do these choices impact the provision of desired physical processes such as sedimentation and wave attenuation?

- How do novel construction materials and designs compare to more conventional materials in terms of shoreline protection and recruitment of habitat-forming species?

ii. Explore Trade-Offs in Achieving Multiple Project Goals Across Varied Hydrogeographic and Socioecological Settings

Advancing the effectiveness of coastal NbS will require that analysis of their service provision encompass a range of metrics applied at greater spatial and temporal scales. The biophysical conditions of shorelines vary geographically along a continuum; for example, coastal settings may be lagoonal, open coast, or deltaic depending on dominant forcings and hydrogeomorphic setting (Rogers, 2017; Yando et al., 2023). Performance of coastal NbS, thereby, depends on their relative position in these settings. For example, an analysis of 52 nature-based shoreline protection projects from around the world found that coral reefs and salt marshes are some of the most effective natural systems for reducing wave heights, but their effectiveness depends on the ratio of wave height to water depth (reefs) or vegetation height (marshes) (Narayan et al., 2016). Mangroves are documented as more effective in sediment accretion than salt marshes, whereas hybrid coastal NbS (ecosystem restoration/creation complemented with an engineered structure) perform better to reduce flood risks than soft coastal NbS (restoration or creation of ecosystems alone) (Huynh et al., 2024). These examples highlight trade-offs between types of ecosystems and interventions to achieve specific goals. Research should focus on understanding the underlying mechanisms that drive observed variation in coastal NbS effectiveness and evaluate them under a variety of settings (Toft et al., 2023). The need for these evaluations is especially dire for understudied settings, such as soft sediment coastlines in the Global South (Yasmeen et al., 2024). Broader quantification of NbS effectiveness across the coastal continuum throughout the world will aid in scaling projects from pilot and local scales to landscape and regional spatial scales.

Key Questions

- What are the distinctions and trade-offs between design elements that prioritize coastal protection versus those that prioritize habitat creation for flora and fauna?
- How does the effectiveness of coastal NbS strategies shift along environmental gradients?

iii. Refine Understanding of Changes in Ecosystem Service Provision Over Time for Varied and Under-Researched Services

As living and changing systems, coastal NbS are expected to be dynamic in their provision of various ecosystem services over time. However, the rate at which many ecological metrics change over time is not well documented in coastal NbS (White et al., 2021). Coastal NbS usually involve the establishment of habitat-forming species, such as marsh vegetation, mangroves, seagrasses, shellfish, or corals, sometimes assisted by engineered structures. The time needed for these communities to establish is inherently affected by the NbS approach, site history, and landscape context (Tomscha & Gergel, 2016; Tomscha et al., 2016). Some NbS projects may strive to reach the functional equivalency of a natural coastal ecosystem, but the timeline needed to achieve these goals far surpasses the timelines for providing coastal protection. One key research gap is simply understanding variability in the rate at which different ecosystem metrics develop after project installation. Previous work in constructed and restored marshes has shown that while many ecological attributes (vegetation diversity, biological productivity, marsh structure) establish quickly after project implementation ($\leq$ 5 years), parameters like soil development (sediment accretion, carbon, organic matter, and microbial processes) may require longer time spans (e.g., a decade or more) (e.g., Ballantine & Schneider, 2009; Chambers et al., 2021; Craft et al., 2002, 2003; Currin et al., 2008; Davis et al., 2015; Isdell et al., 2021; Morris & Staver, 2024). Similarly, La Peyre et al. (2014) demonstrated variability in ecosystem services over time in created oyster reefs. Research is needed to refine these timelines to assess appropriate points for adaptive management intervention and accurately evaluate carbon offsets from projects over time. Creative approaches that accelerate colonization of habitat-forming species have the potential to expedite ecosystem development to better accommodate urgency in coastal resiliency strategies. Recent examples of such research include experimentation on plant preparation techniques (Pausch, 2024), planting configurations (Huang et al., 2022), or placement of structures relative to the elevation of vegetation (Fuentes et al., 2020; Toft et al., 2021).

Key Question

- How do ecological attributes of coastal NbS vary over time? What factors expedite or slow the rates of change for these attributes?

iv. Expand Studies Comparing Coastal NbS with Alternative Approaches

Finally, quantitative comparisons between coastal NbS and traditional shoreline armoring in terms of the provision of ecosystem services are still limited (Huynh et al., 2024; Morris et al., 2018). While shoreline armoring is one approach to reduce the impacts of storm surge, natural coastal ecosystems such as beach dunes and marshes have shown less erosion compared to armored shorelines following storm events (Gittman et al., 2014, 2015). While research has been adept at comparing NbS to control areas without interventions, without direct comparisons between NbS and traditional shoreline armoring, we are ill equipped to assess their efficacy (Morris et al., 2018). As we continue to address gaps in our understanding of the ecological and economic trade-offs between NbS and engineered approaches in the coming decade, Seddon et al. (2020b) recommend focusing on their synergies rather than framing these approaches as alternatives.

Key Questions

- How do novel construction materials and designs compare to more conventional materials in terms of shoreline protection and recruitment of habitat-forming species?
- Under what coastal settings and/or environmental conditions are NbS an effective coastal protection strategy as opposed to traditional shoreline armoring?
- How quickly and to what extent do coastal NbS provide the protections afforded by traditional shoreline armoring? Does the addition of natural components to armored shorelines provide valuable benefits without compromising the performance of the armored structure?

Research for Sustainable Coastal NbS

Persistence of ecosystem service provision and adaptability to change over time (hereby referred to as sustainability) are the cruxes of NbS. Although nature-based coastal protection and habitat creation projects have taken place for decades, unifying them under the term "nature-based solution" has only occurred since 2008 (MacKinnon et al., 2008); meaning that for many of these projects, we are only now reaching the point to assess their performance on a decadal time scale. Lessons from more mature fields, like restoration ecology and ecological succession (Connell & Slayter, 1977; Mori, 2011; Suding, 2011), can be applied to circumvent threats to NbS establishment of self-sustaining biotic communities. As research and implementation in this field flourish, we have opportunities and responsibility to refine the design of coastal NbS now to ensure these projects are long-lived and adaptable for the future.

i. Identify Barriers to Persistence of Ecosystem Service Provision

Newly constructed coastal NbS are initially vulnerable to failure as biological components, such as vegetation, establish (O'Donnell, 2017). Ultimately, the sustainability of coastal NbS depends on the survival and growth of biotic communities beyond this establishment period. Slow rates of species recruitment, low transplant survival, high levels of predation, herbivory, disease, or introduction of invasive species are notable factors that limit the ecosystem's perpetuation (Bilkovic et al., 2021; Suykerbuyk et al., 2016; Vanderklift et al., 2020; Williams & Grosholz, 2008). Failure or degradation of non-living structural components (e.g., cement substrate, coconut fiber logs) over time may compromise the ability for more species to recruit and persist. Unfortunately, many NbS are installed with no long-term monitoring plan to allow managers to counter these threats (Dario et al., 2024). In exemplary cases, coastal NbS projects identify accountable parties to monitor and maintain the project for the foreseeable future. Created marshes in Louisiana typically require a minimum 20-year life span (Coastal Protection & Restoration Authority of Louisiana, 2017, 2023), but this is not the case for all NbS. Monitoring change, specifically degradation, of both coastal NbS structures and biotic communities is an important issue that is currently under-researched.

NbS are frequently evaluated for their abilities to provide specific goal-oriented ecosystem services (Almenar et al., 2021), but ecosystem function is more complex and must be evaluated using a holistic suite of indicators and longer timeframes (Isdell et al., 2021; Yando et al., 2021). Researchers are encouraged to identify the most informative indicators for assessing whether project sustainability is on track. Currently, a plethora of studies exist that focus on primary foundation species as indicators of habitat function in coastal NbS. However, only a few studies have focused on secondary non-focal species. For example, mussels have been documented as direct competitors that threaten the long-term sustainability of living shoreline projects in the Gulf of Mexico, yet in other estuaries, the presence of multiple bivalve species has been shown to enhance project service provision by increasing water filtration (La Peyre et al., 2017; Gedan et al., 2014). These studies demonstrate the importance of non-focal species in the functioning of living shorelines. Although studies have investigated relationships between non-focal species and trophic interactions in ecology in general, this research is still needed in the context of coastal NbS specifically. Rates of elevation change (e.g., subsidence and accretion) can serve as an indicator of how vegetation and other biotic communities shift, but further work is needed to refine these relationships for many species. Perhaps the proximity between coastal NbS and natural habitats influences project longevity, but these questions require long-term monitoring to answer. When long-term on-the-ground monitoring is not feasible, geospatial analysis can be used to hindcast ecological monitoring at large spatial scales (Polk & Eulie, 2018). Long-term monitoring, combined with sharing of lessons learned when projects fail, will enhance identification of failure points for various services, which is crucial to prolong the sustainability of these projects (Bilkovic et al., 2016).

Key Questions

- What is the rate of ecological development for engineered or created coastal NbS?
- When should adaptive management decisions be made to keep created ecosystem trajectories on track?
- Which under-researched taxa serve as indicators of ecological development in variable coastal NbS?

ii. Assess Best Practices for Designing Adaptable NbS to Cope with Environmental Change and Unforeseen Threats

Sustainable coastal NbS must be designed today with the future in mind. Project designs should anticipate expected future changes, including but not limited to sea level rise, increasing oceanic and atmospheric temperatures, increased frequency of coastal storms, and the compounding effects of increasing human development. Quantitative modeling has helped inform how coastal NbS will perform under future scenarios. For example, sustainability of created habitats can be dependent on geophysical features such as landform and fetch (La Peyre et al., 2015; Toft et al., 2023), as well as design features such as the extent of shoreline alteration (Des Roches et al., 2024). Persistence of created ecosystems constrained to narrow intertidal zonation, such as oyster reefs, must also factor in site-specific relative sea level rise rates to ensure biotic communities will be sustained (Ridge et al., 2015). Numerous models have predicted the effects of variable future storm surge and flooding scenarios on coastal ecosystems (Friess et al., 2022; Passeri et al., 2018; Pillai et al., 2022). While several studies have evaluated the shoreline protection capacities of coastal NbS over decadal time spans (Polk & Eulie, 2018; Scyphers et al., 2011; Wellman et al., 2021), there remain many unknowns. The risks and uncertainties associated with NbS sustainability are predicted to increase with rising sea levels (Gijsman et al., 2021; Kwan et al., 2025). Even less understood are the effects of future environmental changes on the complex interactions between ecological, societal, and institutional structures within larger social-ecological systems. While many studies have begun to consider social-ecological dynamics related to coastal sustainability (e.g., Anderies et al., 2019; Glaser & Glaeser, 2014), linked ecosystem-human community model analyses are needed to evaluate human behavioral feedbacks over time (DeAngelis et al., 2020; Hong et al., 2024; Scyphers et al., 2020).

As biological components are key to NbS, their introduction should be done so with attention toward creating resilient communities. Habitat creation projects tend to employ a few selected species suited to deliver a specific goal. Such efforts neglect the importance of biotic interactions at the community level, which could be enhanced by incorporating diverse species to support wider habitat niches and ecosystem resilience (Su et al., 2022). More research is needed to understand how variability in the source populations of biological components may impact the outcomes of coastal NbS. Native ecotypes (genotypes) are adapted to local conditions (Hufford & Mazer, 2003) and have been shown to have greater fitness, adaptability, resilience to disturbance, and resistance to disease compared to their non-local counterparts (Beck & Gustafson, 2012; Bucharova et al., 2017; Durka et al., 2017; Gratani, 2014). For these reasons, some have called for the inclusion of diverse native genotypes in the biological components of coastal NbS design to increase resiliency and adaptation (Cohn et al., 2021). A counter-argument may be to bioengineer species, or select species from non-local populations with more desirable traits, that are better adapted or acclimatized to forecasted conditions. Such efforts have been explored in mollusks (Belgrad et al., 2021), seagrasses (Nimbs et al., 2024), and emergent macrophytic plants (Brancaleoni et al., 2018; Pausch, 2024). The relationships between source population and site-specific fitness and function are critically under-researched for many species. This information is particularly salient in a field where the design and placement of incorporated species (e.g., plant material or oyster seeding) may prioritize cost and logistics versus suitability and population genetics.

Key Questions

- How will sea level rise impact the longevity of NbS designed for current environmental conditions? What considerations need to be made regarding project physical design elements, geophysical site characteristics, and landscape dynamics to ensure coastal NbS longevity in the face of environmental change and anthropogenic activities?

- How do ecological factors such as proximity of source populations, interspecific interactions, population genetics, and genetics of transplanted biota influence the suitability of various coastal NbS strategies and their continued recruitment of habitat-forming species? What ecological design elements maximize or accelerate species recruitment and ecosystem development?
- What factors influence the resilience of coastal NbS following discrete disturbance events, such as storms and heat waves, versus more gradual disturbance threats, such as sea level rise, introduction of invasive species, or increasing urbanization?

iii. Refine Decision Criteria for Assessing When Coastal NbS Are Not Feasible

Although an important tool in the proverbial resilience toolbox, NbS are not the panacea for all problems. It is important to determine where and when these interventions are appropriate. For example, coastal NbS (e.g., mangrove planting with bamboo fences) often require more time and space to reach their full capacity for coastal defense than grey infrastructure (e.g., seawalls, revetments, breakwaters) and may not withstand immediate threats from extreme storm events (Morris et al., 2020; Winterwerp et al., 2020). Coastal habitat creation will be limited by future sea level rise (Saintilan et al., 2023), land-use conflicts (e.g., agriculture, aquaculture, urban development), management priorities (e.g., creating fisheries habitat versus restored habitat, Ellison et al., 2020; Friess et al., 2016), or may not be possible due to extensive shoreline armoring (Friess, 2017). When coastal NbS creation requires a conversion of existing habitat (e.g., fill of subtidal bottom habitats) or impact to adjacent habitats (Smith et al., 2009), conflicts between management goals can obstruct the project. Research is needed to further understand trade-offs between coastal NbS, natural systems, and the built- and socio-economic human environment (Bilkovic & Mitchell, 2013). Research should seek to understand the degree to which coastal NbS services are perceived as substitutable (e.g., aesthetics, recreation, other services would presumably be directly substitutable) or even a disservice (e.g., habitat perceived as source of pests or disease). Ultimately, part of assessing the longevity of coastal NbS in a changing world involves confronting the possibility that, under some circumstances, NbS are not as suitable as traditional shoreline armoring to provide desired protective services in critical timeframes (Firth et al., 2020; La Peyre et al., 2015; Moody et al., 2013).

Key Question

- What factors determine whether the long-term benefits of traditional shoreline armoring outweigh those of a NbS?

Research for Widespread Use of Coastal NbS

Coastal NbS are diverse in their design and can be implemented by a wide range of stakeholders to address different challenges. When adopted by multiple stakeholders across diverse geographic settings (hereby referred to as widespread), their benefits may be maximized. However, misconceptions and uncertainties around coastal NbS threaten widespread adoption of these approaches (Mednikova et al., 2023; O'Leary et al., 2023, Guthrie et al., 2023). Public and political support for coastal NbS depends on bridging the science-to-practice communication gap. This bridge requires transfer of knowledge and best practices between NbS practitioners and decision-makers, integration of stakeholder perceptions and preferences into coastal management, and advancing economic valuation of NbS. There are several means by which the research community can assist in providing the building blocks needed to support widespread use of coastal NbS. Here, we share our perspectives on areas on which researchers should focus to address these limitations and share case study examples of successes, while acknowledging that many in this field already employ these practices.

i. Understand and Improve Best Practices for Transdisciplinary Communication and Knowledge Transfer

Smith et al. (2020) identified that the lack of accessibility to scientific journal articles by practitioners and managers is one barrier to communicating NbS science. While Smith et al. (2020) recommended increasing funding for publication in open access journals, researchers also should communicate findings via other mediums (e.g., conferences, professional workshops, trade and other non-academic publications, web-based resources, public outreach events, relationships with practitioners and municipalities, or serving as a technical advisor to policy). Other studies recommend establishing transdisciplinary networks to encourage the use of science-based NbS (Mednikova et al., 2023). One example of such a networking tool is the National Spatial Data Infrastructure system for NbS co-benefits, a GIS tool that accumulates comprehensive multidisciplinary datasets for NbS in the U.S. (Castro & Rifai, 2021). Another example of a species-specific network is the Native Olympia Oyster Collaborative (NOOC), which has the mission to maintain a network of oyster scientists, practitioners, educators, and aquaculturists. NbS communities of practice can provide a mechanism to scale up implementation of NbS in a science-based, coordinated way. These collaboratives can create the "safe" space needed to facilitate dialogues among different groups on project failures and successes, share resources, and develop best practices. One example is the Coastal Zone

Canada Association that supports regional coastal NbS community of practice groups to share knowledge and support the development of design standards (https://coastalzonecanada.org/nbcs/). Another example is Florida's regional Estuarine Restoration Teams, informal groups of practitioners (including Federal and State agencies, universities, NGOs, and private firms) that serve as working groups to share ideas and plan and implement estuarine restoration at the aquascape scale within their respective regions (V. Encomio, personal communication).

Key Questions

- What are the best practices for facilitating communication between science, practice, and policy regarding coastal NbS? Where are barriers to knowledge transfer?
- How can project success stories and challenges encountered be communicated to obtain support for monitoring and assessment?

ii. Advance Best Practices for Implementation of Training Programs, Guideline Development, and Materials Used to Support the Implementation of NbS

Implementation of NbS also depends on the available workforce. Although not a limiting factor in every coastal region, the need to scale up training programs specifically designed to educate and train professionals working in coastal NbS (e.g., landscapers, engineers, marine contractors, landscape architects, urban planners, policy makers, and local government resilience and sustainability managers) has been recognized as a global limitation to the implementation of NbS (Davies & Lafortezza, 2019; Morris et al., 2024). Previous successes in addressing this need include Sea Grant and state partners in the U.S. that have developed trainings specifically targeted toward those industries (Martin et al., 2024; North Carolina Living Shorelines Academy, 2024). Professional training programs, such as in the Chesapeake Bay region (e.g., Chesapeake Bay Landscape Professionals (2024)), and national-level certifications (e.g., Waterfront Edge Design Guidelines; Waterfront Alliance, 2024) provide models for developing training and implementation standards that can be applied at multiple scales. Further, development of decision-making tools and guidelines, geared toward diverse stakeholders, is needed to determine coastal NbS site suitability. Examples of these guidelines include the Shoreline Management Model, which has been adapted for use in many coastal regions in the United States (Nunez et al., 2022) and Temmerman et al.'s (2023) comprehensive modeling of risk reduction provided by tidal marshes and mangroves. The Nature Conservancy developed a mangrove restoration potential mapping tool (https://maps.coastalresilience.org/mangrove-restoration/) to identify areas with the highest restoration potential, considering ecological, socio-economic, and environmental factors (Worthington and Spalding, 2018).

Widespread implementation of coastal NbS also depends on the availability of materials from the industries that underlie project construction. Materials may include plants that are genetically diverse, sourced from local provenances, or strains with desirable traits (Bhatt et al., 2022; Reynolds et al., 2012; Ryan et al., 2007), uncontaminated local sediment (Bell et al., 2021; Piercy et al., 2023), biosecure bivalve shell (Fitzsimons et al., 2020), sediment trapping structures (Eichmanns et al., 2021), or desired genotypes of reef-building species (Howie & Bishop, 2021). Researchers and practitioners working in coastal NbS need to communicate with these industries to develop a common understanding of the preferred product specifications and barriers to production. These industries may require additional financial support and reliable forecasts of material demands to scale up their production. There exist many opportunities for research to build upon existing knowledge of best material specifications for projects as well as how to best address economic, logistical, or communication barriers to sourcing those materials.

Key Questions

- What are recommendations, or model case studies, for coastal NbS training and workforce development programs? How can these programs be adapted for other regions/industries?
- What decision-making tools and guides exist for policymakers and professionals? What are the most useful universal methods to evaluate the effectiveness of these decision-making tools for expanding use of coastal NbS? How can science, policy, and practitioners facilitate the underlying industries that support coastal NbS?
- How can coastal NbS be scaled up from local-scale case studies to broadscale implementation?
- What are the best practices for identifying or developing sources of materials for the implementation of coastal NbS (e.g., shell, plant sources, and sediment fill)?

iii. Understand Differences in Stakeholder Perceptions and Preferences that Influence NbS Decisions

The decision to implement NbS depends on multiple factors, including whether it is an individual or group decision, prior experiences, belief, culture, and economics (Bennett, 2016; Guthrie et al., 2023; Mukherjee et al., 2016; Scyphers et al., 2015). Individual perception of coastal NbS can be highly influenced, for example, by both external opinions and individual knowledge of local coastal management initiatives (Barry et al., 2024; Dario et al., 2024; Josephs & Humphries, 2018; Leichenko et al., 2018; Scyphers et al., 2015). Understanding factors influencing NbS decisions within multiple socioeconomic and environmental contexts can provide insight into effective ways to drive behavior toward NbS use (e.g., targeted messaging, policy actions, financial incentives). NbS effectiveness, costs, and time scales can be important decision factors (Chairat & Gheewala, 2024). Research on coastal community perceptions and preferences is needed to inform the development of decision tools to evaluate trade-offs in project types over multiple spatiotemporal scales (Smith et al., 2017).

Involving diverse stakeholders throughout a coastal NbS project is crucial to building popular and political support. We encourage engaging property owners, regulators, practitioners, policy makers, industry, Tribal and Indigenous communities and Traditional Owners, and community members, in the co-production of coastal NbS priorities to ensure the project meets the community's goals (i.e., effectiveness) and ties directly into their persistence (i.e., sustainability). From conceptualization to post-installation monitoring and adaptive management, active participation fosters investment and commitment while imparting transparency and legitimacy to the decisions made. Engaging all partners in conceptualization and planning with multi-criteria frameworks and Q-methodology (a mixed methods approach used to study subjective opinions) can facilitate multifaceted decision-making and increase acceptance across groups with disparate interests (Apine & Stojanovic, 2024; Ferreira et al., 2020; Giordano et al., 2020; Ruangpan et al., 2021).

Key Question

- How do various stakeholders differentially value the coastal protection services of NbS compared to other ecosystem services? What drives these discrepancies?

iv. Advance Economic Valuation of NbS for Improved Trade-Off Assessment in Support of Policy Development, Governance, and Decisions

Coastal natural capital assets are not fully recognized or included in traditional economic accounting, challenging sustainable development globally (Fenichel et al., 2020). While there are national natural capital accounting efforts underway (e.g., Friess et al., 2020; Thiagarajah et al., 2015; Wielgus et al., 2023), variability in the valuation of NbS is driven by local environmental conditions and human perceptions and behaviors. There is a need to develop natural capital accounting frameworks for coastal NbS that capture the heterogeneity in ecosystem service provision and valuation (Guerry et al., 2015). Additional site-specific studies that model behavioral responses in response to storm and flood risk (e.g., install NbS, armor shoreline, or do nothing) can be used to understand community-scale trade-offs and inform value estimates that can be generalized to similar coastal communities. Numerical physical modeling paired with models of economic behavior can be further used to simulate future scenarios of coastal NbS benefits (e.g., Kwan et al., 2025; Stewart-Sinclair et al., 2021; van Zelst et al., 2021). Assessing the monetary value of coastal NbS ecosystem services can be used to guide policy and management decisions, inform market development (e.g., blue carbon trading, Koh et al., 2021; Macreadie et al., 2021), and increase awareness and motivation to use NbS (Ng et al., 2023; Scheld et al., 2024; Ying et al., 2024).

Key Questions

- How can different stakeholder needs and values be best shared with the research community to promote and guide actionable research?
- What increases stakeholder confidence in coastal NbS (e.g., empirical research, first-hand experience, input from trusted individuals, consistency of results), and conversely, how does uncertainty in science influence stakeholder perception? How is public support developed?

Conclusion

The aforementioned research questions represent priority focal areas to advance (1) the effectiveness, (2) sustainability, and (3) widespread adoption of coastal NbS. As with any attempt to identify priority research questions in a manner of broad interest to this field, the complexities of the individual research questions are simplified (Sutherland et al., 2009). We recognize that the research and professional communities working in coastal NbS are both discipline-rich and globally expansive. Thus, research on topics covered here may already exist or be in a state of progress; however, refinement of all research answers is needed for the intricacies of site-specific and regional conditions. Properly addressing these research gaps will require diversity in terms of the disciplines involved, stakeholders consulted, and geographic regions tested. We have applied our research gap framework (Fig. 1) to develop specific research questions for a range of coastal NbS projects across various global regions (Supplementary Figs. 1–3) as demonstration for adoption by others. At the midpoint in this decade on ecosystem restoration, we hope our perspectives provide cause for reflection on how far research in this young field has come as well as a re-evaluation of the direction for transdisciplinary future research.

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Declarations

Competing Interests The authors declare no competing interests.

References

Almenar, J. B., Elliot, T., Rugani, B., Philippe, B., Gutierrez, T. N., Sonnemann, G., & Geneletti, D. (2021). Nexus between nature-based solutions, ecosystem services and urban challenges. *Land Use Policy, 100*, 104898. https://doi.org/10.1016/j.landusepol.2020.104898

Anderies, J. M., Barreteau, O., & Brady, U. (2019). Refining the robustness of social-ecological systems framework for comparative analysis of coastal system adaptation to global change. *Regional Environmental Change, 19*(7), 1891–1908. https://doi.org/10.1007/s10113-019-01529-0

Apine, E., & Stojanovic, T. (2024). Is the coastal future green, grey or hybrid? Divers perspectives on coastal flood risk management and adaptation in the UK. *Cambridge Prisms: Coastal Futures, 2*, e4. https://doi.org/10.1017/cft.2024.4

Arkema, K. K., Griffin, R., Maldonado, S., Silver, J., Suckale, J., & Guerry, A. D. (2017). Linking social, ecological, and physical science to advance natural and nature-based protection for coastal communities. *Annals of the New York Academy of Sciences, 1399*(1), 5–26. https://doi.org/10.1111/nyas.13322

Ballantine, K., & Schneider, R. (2009). 55 years of soil development in restored fresh-water depressional wetlands. *Ecological Applications, 19*, 1467–1480. https://doi.org/10.1890/07-0588.1

Barry, S. C., Reynolds, L. K., Braswell, A. E., Gittman, R. K., Scyphers, S. B., & Smyth, A. R. (2024). Perceived effectiveness drives shoreline decision-making for Florida's waterfront property owners. *Ocean and Coastal Management, 258*, 107353. https://doi.org/10.1016/j.ocecoaman.2024.107353

Barry, S. C., Hernandez, E. M., & Clark, M. W. (2025). Performance assessment of three living shorelines in Cedar Key, Florida, USA. *Estuaries and Coasts, 48*, 7. https://doi.org/10.1007/s12237-024-01440-w

Beck, J., & Gustafson, D. (2012). Plant source influence on Spartina alterniflora survival and growth in restored South Carolina salt marshes. *Southeastern Naturalist, 11*(4), 747–754. https://doi.org/10.1656/058.011.0412

Belgrad, B. A., Combs, E. M., Walton, W. C., & Smee, D. L. (2021). Use of predator cues to bolster oyster resilience for aquaculture and reef restoration. *Aquaculture, 538*, Article 736553. https://doi.org/10.1016/j.aquaculture.2021.736553

Bell, K. S., Boyd, B. M., Goetz, S. L., Hayes, D. F., Magar, V. S., & Suedel, B. (2021) Overcoming barriers to beneficial use of dredged material in the US. Proceedings of Dredging Summit & Expo 2021. *WEDA Journal of Dredging, 19*(2). https://westerndredging.org/phocadownload/2021_Virtual/Proceedings/2A-4.pdf

Bennett, N. J. (2016). Using perceptions as evidence to improve conservation and environmental management. *Conservation Biology, 30*, 582–592. https://doi.org/10.1111/cobi.12681

Bhatt, A., Gallacher, D. J., Jarma-Orozco, A., Fernandes, D., & Pompelli, M. F. (2022). Seed provenance selection of wild halophyte seeds improves coastal rehabilitation efficiency. *Estuarine, Coastal and Shelf Science, 265*, 107657. https://doi.org/10.1016/j.ecss.2021.107657

Bianciardi, A., N. Beccattini, & G. Cascini. (2024). How would nature design and implement nature-based solutions? *Nature-Based Solutions*, 3. https://doi.org/10.1016/j.nbsj.2022.100047

Bilkovic, D. M., & Mitchell, M. M. (2013). Ecological tradeoffs of stabilized salt marshes as a shoreline protection strategy: Effects of artificial structures on microbenthic assemblages. *Ecological Engineering, 61*, 469–481. https://doi.org/10.1016/j.ecoleng.2013.10.011

Bilkovic, D. M., Mitchell, M., Mason, P., & Duhring, K. (2016). The role of living shorelines as estuarine habitat conservation strategies. *Coastal Management, 44*(3), 161–174. https://doi.org/10.1080/08920753.2016.1160201

Bilkovic, D. M., Mitchell, M. M., La Peyre, M. K., & Toft, T. J. (Eds.). (2017). *Living shorelines: The science and management of nature-based coastal protection*. CRC Press.

Bilkovic, D. M., Isdell, R. E., Guthrie, A. G., Mitchell, M. M., & Chambers, R. M. (2021). Ribbed mussel Geukensia demissa population response to living shoreline design and ecosystem development. *Ecosphere, 12*(3), e03402. https://doi.org/10.1002/ecs2.3402

Brancaleoni, L., Gerdol, R., Abeli, T., Corli, A., Rossi, G., & Orsenigo, S. (2018). Nursery pre-treatment positively affects reintroduced plant performance via plant pre-conditioning, but not via maternal effects. *Aquatic Conservation: Marine and Freshwater Ecosystems, 28*(3), 641–650. https://doi.org/10.1002/aqc.2888

Bucharova, A., Michalski, S., Hermann, J.-M., Heveling, K., Durka, W., Hölzel, N., Kollmann, J., & Bossdorf, O. (2017). Genetic differentiation and regional adaptation among seed origins used for grassland restoration: Lessons from a multi-species transplant experiment. *Journal of Applied Ecology, 54*, 127–136. https://doi.org/10.1111/1365-2664.12645

Castro, C. V., & Rifai, H. S. (2021). Development and assessment of a web-based national spatial data infrastructure for nature-based solutions and their social, hydrological, ecological, and environmental co-benefits. *Sustainability, 13*(19), 11018. https://doi.org/10.3390/su131911018

Castro, C. V., & H. S. Rifai. (2024). The conceptual quantitative assessment framework for nature-based solutions (NbS). *Nature-Based Solutions*, p.100152. https://doi.org/10.1016/j.nbsj.2024.100152

Chambers, R. M., Gorsky, A. L., Isdell, R. E., Mitchell, M. M., & Bilkovic, D. M. (2021). Comparison of nutrient accrual in constructed living shoreline and natural fringing marshes. *Ocean & Coastal Management, 199*, 105401. https://doi.org/10.1016/j.ocecoaman.2020.105401

Chesapeake Bay Landscape Professionals. (2024). Chesapeake Bay Landscape Professional Living Shoreline Training certificate (CBLP-Shorelines). Last accessed: 28 May 2024. Source: https://certified.cblpro.org/cblp-shorelines/

Coastal Protection and Restoration Authority of Louisiana. (2017). Louisiana's comprehensive master plan for a sustainable coast, 3rd edition. Coastal Protection and Restoration Authority of Louisiana. Baton Rouge, LA. Source: https://Coastal.la.gov

Coastal Protection and Restoration Authority of Louisiana. (2023). Louisiana's comprehensive master plan for a sustainable coast, 4th edition. Coastal Protection and Restoration Authority of Louisiana. Baton Rouge, LA. Source: https://Coastal.la.gov

Cohn, J. L., Copp Franz, S., Mandel, R. H., Nack, C. C., Brainard, A. S., Eallonardo, A., & Magar, V. (2021). Strategies to work towards long-term sustainability and resiliency of nature-based solutions in coastal environments: A review and case studies. *Integrated Environmental Assessment and Management, 18*(1), 123–134. https://doi.org/10.1002/ieam.4484

Connell, J. H., & Slayter, R. O. (1977). Mechanisms of succession in natural communities and their role in community stability and organization. *Am. Natural., 111*, 1119–1144. https://doi.org/10.1086/283241

Craft, C., Broome, S., & Campbell, C. (2002). Fifteen years of vegetation and soil development after brackish-water marsh creation. *Restoration Ecology, 10*(2), 248–258. https://doi.org/10.1046/j.1526-100X.2002.01020.x

Craft, C., Megonigal, P., Broome, S., Stevenson, J., Freese, R., Cornell, J., ... & Sacco, J. (2003). The pace of ecosystem development of constructed Spartina alterniflora marshes. *Ecological Applications*, *13*(5), 1417–1432. https://doi.org/10.1890/02-5086

Currin, C. A., Delano, P. C., & Valdes-Weaver, L. M. (2008). Utilization of a citizen monitoring protocol to assess the structure and function of natural and stabilized fringing salt marshes in North Carolina. *Wetlands Ecology and Management, 16*, 97–118. https://doi.org/10.1007/s11273-007-9059-1

Dario, C., Curley, C., & Mach, K. J. (2024). Shaping coastal nature-based solutions: Perceptions and policy priorities of living shorelines. *Nature-Based Solutions, 6*, 100179. https://doi.org/10.1016/j.nbsj.2024.100179

Davies, C., & Lafortezza, R. (2019). Transitional path to the adoption of nature-based solutions. *Land Use Policy, 80*, 406–409. https://doi.org/10.1016/j.landusepol.2018.09.020

Davis, J. L., Currin, C. A., O'Brien, C., Raffenburg, C., & Davis, A. (2015). Living shorelines: Coastal resilience with a blue carbon benefit. *PLoS ONE, 10*(11), e0142595. https://doi.org/10.1371/journal.pone.0142595

Davis, J., Currin, C., & Mushegian, N. (2022). Effective use of thin layer sediment application in *Spartina alterniflora* marshes is guided by elevation-biomass relationship. *Ecological Engineering, 177*, 106566. https://doi.org/10.1016/j.ecoleng.2022.106566

DeAngelis, B. M., Sutton-Grier, A. E., Colden, A., Arkema, K. K., Baillie, C. J., Bennett, R. O., Benoit, J., Blitch, S., Chatwin, A., Dausman, A., Gittman, R., Greening, H., Henkel, J., Houge, R., Howard, R., Hughes, A., Lowe, J., Scyphers, S., Sherwood, E., … Grabowski, J. H. (2020). Social factors key to landscape-scale coastal restoration: Lessons learned from three US case studies. *Sustainability, 12*(3), 869. https://doi.org/10.3390/su12030869

Des Roches, S., Accola, K. L., Faulkner, H. S., Morgan, J. R., Perla, B. S., Metler, M., Dethier, M. N., & Toft, J. D. (2024). Shoreline restoration including armor removal and log placement affect ecosystem recovery through time. *Restoration Ecology, 32*(4), e14097. https://doi.org/10.1111/rec.14097

Doelle, M., & Puthucherril, T.G. (2023) Nature-based solutions to sea level rise and other climate change impacts on oceanic and coastal environments: A law and policy perspective. *Nordic Journal of Botany*. E03051. https://doi.org/10.1111/njb.03051

Dunlop, T. (2016). Optimal oyster reef design for shoreline protection using combinations of oyster shell filled bags and sandbags (Doctoral dissertation, Honours Thesis, UNSW Sydney).

Durka, W., Michalski, S. G., Berendzen, K. W., Bossdorf, O., Bucharova, A., Hermann, J. M., Hölzel, N., & Kollmann, J. (2017). Genetic differentiation within multiple common grassland plants supports seed transfer zones for ecological restoration. *Journal of Applied Ecology, 54*(1), 116–126. https://doi.org/10.1111/1365-2664.12636

Eichmanns, C., Lechthaler, S., Zander, W., Pérez, M. V., Blum, H., Thorenz, F., & Schüttrumpf, H. (2021). Sand trapping fences as a nature-based solution for coastal protection: An international review with a focus on installations in Germany. *Environments, 8*(12), 135. https://doi.org/10.3390/environments8120135

Ellison, A. M., Felson, A. J., & Friess, D. A. (2020). Mangrove rehabilitation and restoration as experimental adaptive management. *Frontiers in Marine Science, 7*, 327. https://doi.org/10.3389/fmars.2020.00327

Familkhalili, R., Davis, J., Currin, C. A., Heppe, M. E., Cohen, S., & S. (2023). Quantifying the benefits of wetland restoration under projected sea level rise. *Frontiers in Marine Science, 10*, 1187276. https://doi.org/10.3389/fmars.2023.1187276

Favero, F., & Hinkel, J. (2024). Key innovations in financing nature-based solutions for coastal adaptation. *Climate, 12*(4), 53. https://doi.org/10.3390/cli12040053

Fenichel, E. P., Addicott, E. T., Grimsrud, K. M., Lange, G. M., Porras, I., & Milligan, B. (2020). Modifying national accounts for sustainable ocean development. *Nature Sustainability, 3*(11), 889–895. https://doi.org/10.1038/s41893-020-0592-8

Ferreira, V., Barreira, V. P., Loures, L., Antunes, D., & Panagopoulos, T. (2020). Stakeholders' engagement on nature-based solutions: A systematic literature review. *Sustainability, 12*(2), 640. https://doi.org/10.3390/su12020640

Firth, L. B., Airoldi, L., Bulleri, F., Challinor, S., Chee, S. Y., Evans, A. J., Hanley, M. E., Knights, A. M., O'Shaughnessy, K., Thompson, R. C., & Hawkins, S. J. (2020). Greening of grey infrastructure should not be used as a Trojan horse to facilitate coastal development. *Journal of Applied Ecology, 57*, 1762–1768. https://doi.org/10.1111/1365-2664.13683

Fitri, A., Hashim, R., Song, K. I., & Motamedi, S. (2015). Evaluation of morphodynamic changes in the vicinity of low-crested breakwater on cohesive shore of Carey Island. *Malaysia. Coastal Engineering Journal, 57*(04), 1550023. https://doi.org/10.1142/S0578563415500230

Fitzsimons, J. A., Branigan, S., Gillies, C. L., Brumbaugh, R. D., Cheng, J., DeAngelis, B. M., ... & Zu Ermgassen, P. S. (2020). Restoring shellfish reefs: Global guidelines for practitioners and scientists. *Conservation Science and Practice*, *2*(6), e198. https://doi.org/10.1111/csp2.198

Friess, D. A. (2017). Singapore as a long-term case study for tropical urban ecosystem services. *Urban Ecosystems, 20*(2), 277–291.

Friess, D. A., Thompson, B. S., Brown, B., Amir, A. A., Cameron, C., Koldewey, H. J., Sasmito, S. D., & Sidik, F. (2016). Policy challenges and approaches for the conservation of mangrove forests in Southeast Asia. *Conservation Biology, 30*(5), 933–949.

Friess, D. A., Yando, E. S., Wong, L. W., & Bhatia, N. (2020). Indicators of scientific value: An under-recognised ecosystem service of coastal and marine habitats. *Ecological Indicators, 113*, 106255. https://doi.org/10.1016/j.ecolind.2020.106255

Friess, D. A., Adame, M. F., Adams, J. B., & Lovelock, C. E. (2022). Mangrove forests under climate change in a 2 C world. *Wiley Interdisciplinary Reviews: Climate Change, 13*(4), e792. https://doi.org/10.1002/wcc.792

Fuentes, C., Whitcraft, C. R., & Zacherl, D. (2020). Adaptive restoration reveals potential effect of tidal elevation on oyster restoration outcomes. *Wetlands, 40*(2), 93–99. https://doi.org/10.1007/s13157-019-01166-7

Gedan, K. B., Kellogg, L., & Breitburg, D. L. (2014). Accounting for multiple foundation species in oyster reef restoration benefits. *Restoration Ecology, 22*, 517–552. https://doi.org/10.1111/rec.12107

Gijsman, R., Horstman, E. M., van der Wal, D., Friess, D. A., Swales, A., & Wijnberg, K. M. (2021). Nature-based engineering: A review on reducing coastal flood risk with mangroves. *Frontiers in Marine Science, 8*, 702412. https://doi.org/10.3389/fmars.2021.702412

Giordano, R., Pluchinotta, I., Pagano, A., Scrieciu, A., & Nanu, F. (2020). Enhancing nature-based solutions acceptance through stakeholders' engagement in co-benefits identification and trade-offs analysis. *Science of the Total Environment, 713*, 136552. https://doi.org/10.1016/j.scitotenv.2020.136552

Gittman, R. K., Popowich, A. M., Bruno, J. F., & Peterson, C. H. (2014). Marshes with and without sills protect estuarine shorelines from erosion better than bulkheads during a category 1 hurricane. *Ocean & Coastal Management, 102*, 94–102.

Gittman, R. K., Fodrie, F. J., Popowich, A. M., Keller, D. A., Bruno, J. F., Currin, C. A., ... & Piehler, M. F. (2015). Engineering away our natural defenses: An analysis of shoreline hardening in the US. Frontiers in Ecology and the Environment, 13(6), 301–307.

Glaser, M., & Glaeser, B. (2014). Towards a framework for cross-scale and multi-level analysis of coastal and marine social-ecological systems dynamics. *Regional Environmental Change, 14*(6), 2039–2052. https://doi.org/10.1007/s10113-014-0637-5

Gratani, L. (2014). Plant phenotypic plasticity in response to environmental factors. Advances in Botany. 2014, Article ID 208747, 17. https://doi.org/10.1155/2014/208747

Guerry, A. D., Polasky, S., Lubchenco, J., Chaplin-Kramer, R., Daily, G. C., Griffin, R., Ruckelshaus, M., Bateman, I. J., Duraiappah, A., Elmqvist, T., & Feldman, M. W. (2015). Natural capital and ecosystem services informing decisions: From promise to practice. *Proceedings of the National Academy of Sciences of the United States of America, 112*(24), 7348–7355. https://doi.org/10.1073/pnas.1503751112

Guthrie, A. G., Stafford, S., Scheld, A. M., Nunez, K., & Bilkovic, D. M. (2023). Property owner shoreline modification decisions vary based on their perceptions of shoreline change and interests in ecological benefits. *Frontiers in Marine Science, 10*, 1031012. https://doi.org/10.3389/fmars.2023.1031012

Hong, W., Zhao, Y., Yang, S., Yang, X., Li, Y., & Wang, C. (2024). An analytical framework based on social-ecological systems for identifying priority areas for ecological restoration in coastal regions. *Journal of Environmental Management, 370*, 122958. https://doi.org/10.1016/j.jenvman.2024.122958

Howie, A. H., & Bishop, M. J. (2021). Contemporary oyster reef restoration: Responding to a changing world. *Frontiers in Ecology and Evolution, 9*, 689915. https://doi.org/10.3389/fevo.2021.689915

Huang, H., Xu, C., & Liu, Q. X. (2022). 'Social distancing' between plants may amplify coastal restoration at early stage. *Journal of Applied Ecology, 59*(1), 188–198. https://doi.org/10.1111/1365-2664.14044

Huff, T. P., Feagin, R. A., & Figlus, J. (2022). Delft3D as a tool for living shoreline design selection by coastal managers. *Frontiers in Built Environment, 8*, 926662. https://doi.org/10.3389/fbuil.2022.926662

Hufford, K., & Mazer, S. (2003). Plant ecotypes: Genetic differentiation in the age of ecological restoration. *Trends in Ecology and Evolution, 15*, 147–155.

Huynh, L. T. M., Su, J., Wang, Q., Stringer, L. C., Switzer, A. D., & Gasparatos, A. (2024). Meta-analysis indicates better climate adaptation and mitigation performance of hybrid engineering-natural coastal defence measures. *Nature Communications, 15*(1), 2870. https://doi.org/10.1038/s41467-024-46970-w

Isdell, R. E., Bilkovic, D. M., Guthrie, A. G., Mitchell, M. M., Chambers, R. M., Leu, M., & Hershner, C. (2021). Living shorelines achieve functional equivalence to natural fringe marshes across multiple ecological metrics. *PeerJ, 9*, e11815. https://doi.org/10.7717/peerj.11815

IUCN (International Union for Conservation of Nature). (2020). Global standard for nature-based solutions. A user-friendly framework for the verification, design and scaling up of NbS. First edition. Gland, Switzerland: IUCN. https://doi.org/10.2305/IUCN.CH.2020.08.en

Jordan, P., & Fröhle, P. (2022). Bridging the gap between coastal engineering and nature conservation? A review of coastal ecosystems as nature-based solutions for coastal protection. *Journal of Coastal Conservation, 26*(2), 4. https://doi.org/10.1007/s11852-021-00848-x

Josephs, L. I., & Humphries, A. T. (2018). Identifying social factors that undermine support for nature-based coastal management. *Journal of Environmental Management, 212*, 32–38. https://doi.org/10.1016/j.jenvman.2018.01.085

Kibler, K. M., M. Donnelly, D. Cannon, J. Phagan, L. Walters, G. McClenachan, & A. Roddenberry, (2020). Developing a shoreline restoration suitability model for North Indian River and Mosquito Lagoon, Phase II. Indian River Lagoon National Estuaries Program Report IRL2018–017, March 2020.

Koh, L. P., Zeng, Y., Sarira, T. V., & Siman, K. (2021). Carbon prospecting in tropical forests for climate change mitigation. *Nature Communications, 12*(1), 1271. https://doi.org/10.1038/s41467-021-21560-2

Kwan, V., Friess, D. A., Sarira, T. V., & Zeng, Y. (2025). Permanence risks limit blue carbon financing strategies to safeguard Southeast Asian mangroves. *Communications Earth & Environment, 6*(1), 57. https://doi.org/10.1038/s43247-025-02035-4

La Peyre, M. K., Humphries, A. T., Casas, S. M., & La Peyre, J. F. (2014). Temporal variation in development of ecosystem services from oyster reef restoration. *Ecological Engineering, 63*, 34–44. https://doi.org/10.1016/j.ecoleng.2013.12.001

La Peyre, M. K., Serra, K., Joyner, T. A., & Humphries, A. (2015). Assessing shoreline exposure and oyster habitat suitability maximizes potential success for sustainable shoreline protection using restored oyster reefs. *PeerJ, 3*, e1317. https://doi.org/10.7717/peerj.1317

La Peyre, M. K., Miller, L. S., Miller, S., & Melancon, E. (2017). Comparison of oyster populations, shoreline protection service, and site characteristics at seven created fringing reefs in Louisiana: Key parameters and responses to consider. In *Living Shorelines* (pp. 363–382). CRC Press.

Leichenko, R., McDermott, M., & Bezborodko, E. (2018). Barriers, limits and limitations to resilience. In P. C. Heidkamp & J. Morrissey (Eds.), *Towards Coastal Resilience and Sustainability* (1st ed.). Routledge. https://doi.org/10.4324/9780429463723

MacKinnon, K., Sobrevila, C., & Hickey, V. (2008). Biodiversity, climate change, and adaptation: Nature-based solutions from the World Bank portfolio (No. 46726, pp. 1–112). The World Bank.

Macreadie, P.I., Costa, M.D., Atwood, T.B., Friess, D.A., Kelleway, J.J., Kennedy, H., Lovelock, C.E., Serrano, O. & Duarte, C.M. (2021). Blue carbon as a natural climate solution. *Nature Reviews Earth & Environment*, *2*(12), pp.826–839. https://www.nature.com/articles/s43017-021-00224-1

Mai Van, C., Ngo, A., Mai, T., & Dao, H. T. (2021). Bamboo fences as a nature-based measure for coastal wetland protection in Vietnam. *Frontiers in Marine Science, 8*, 756597. https://doi.org/10.3389/fmars.2021.756597

Marino, M., Nasca, S., Alkharoubi, A. I., Cavallaro, L., Foti, E., & Musumeci, R. E. (2025). Efficacy of nature-based solutions for coastal protection under a changing climate: A modelling approach. *Coastal Engineering*, 104700. https://doi.org/10.1016/j.coastaleng.2025.104700

Martin, S., Barry, S. C., Ubeda, A. J., Encomio, V., Clark, M. W., O'Connor, R., Baily, M. S., & Sparks, E. (2024). Reducing barriers to living shorelines through Sea Grant extension programs. *Oceanography*, *37*(1), 129–133. https://www.jstor.org/stable/27301103

Moody, R. M., Cebrian, J., Kerner, S. M., Heck, K. L., Powers, S. P., & Ferraro, C. (2013). Effects of shoreline erosion on salt-marsh floral zonation. *Marine Ecology Progress Series, 488*, 145–155. https://doi.org/10.3354/meps10404

Moraes, R. P., Reguero, B. G., Mazarrasa, I., Ricker, M., & Juanes, J. A. (2022). Nature-based solutions in coastal and estuarine areas of Europe. *Frontiers in Environmental Science, 10*, 829526. https://doi.org/10.3389/fenvs.2022.829526

Mori, A. S. (2011). Ecosystem management based on natural disturbances: Hierarchical context and non-equilibrium paradigm. *Journal of Applied Ecology, 48*, 280–292. https://doi.org/10.1111/j.1365-2664.2010.01956.x

Morris, J. T., & Staver, L. W. (2024). Elevation changes in restored marshes at Poplar Island, Chesapeake Bay, MD: II. Modeling the importance of marsh development time. *Estuaries and Coasts, 47*, 1799–1813. https://doi.org/10.1007/s12237-024-01342-x

Morris, R. L., Konlechner, T. M., Ghisalberti, M., & Swearer, S. E. (2018). From grey to green: Efficacy of eco-engineering solutions for nature-based coastal defence. *Global Change Biology, 24*(5), 1827–1842. https://doi.org/10.1111/gcb.14063

Morris, R. L., Bilkovic, D. M., Walles, B., & Strain, E. M. (2022). Nature-based coastal defence: Developing the knowledge needed for wider implementation of living shorelines. *Ecological Engineering, 185*, 106798. https://doi.org/10.1016/j.ecoleng.2022.106798

Morris, R.L., Boxshall, A., & Swearer, S. E. (2020). Climate-resilient coasts require diverse defence solutions. *Nature Climate Change*, 10(6), pp.485–487. https://www.nature.com/articles/s41558-020-0798-9

Morris, R. L., La Peyre, M. K., Webb, B. M., Marshall, D. A., Bilkovic, D. M., Cebrian, J., ... & Swearer, S. E. (2021). Large-scale variation in wave attenuation of oyster reef living shorelines and the influence of inundation duration. *Ecological Applications*, *31*(6), e02382. https://doi.org/10.1002/eap.2382

Morris, R. L., Pomeroy, A. W., Boxshall, A., Colleter, G., Dack, D., Dunlop, A. R., ... & Swearer, S. E. (2024). A blueprint for overcoming barriers to the use of nature-based coastal protection in Australia. *Frontiers in Environmental Science,* 12, 1435833. https://doi.org/10.3389/fenvs.2024.1435833

Mukherjee, N., Dicks, L. V., Shackelford, G. E., Vira, B., & Sutherland, W. J. (2016). Comparing groups versus individuals in decision making: A systematic review protocol. *Environmental Evidence, 5*, 1–9. https://doi.org/10.1186/s13750-016-0066-7

Narayan, S., Beck, M. W., Reguero, B. G., Losada, I. J., Van Wesenbeeck, B., Pontee, N., ... & Burks-Copes, K. A. (2016). The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PloS one*, *11*(5), e0154735. https://doi.org/10.1371/journal.pone.0154735

Ng, N. C. S. L., Toh, T. C., Toh, K. B., Sam, S. Q., Kikuzawa, Y. P., Chou, L. M., & Huang, D. (2023). Enhancing reef restoration by assessing stakeholder knowledge, attitudes, and preferences. *Restoration Ecology, 31*(5), e13854. https://doi.org/10.1111/rec.13854

Nimbs, M. J., Glasby, T. M., Sinclair, E. A., Swadling, D., Davis, T. R., & Coleman, M. A. (2024). A donor registry: Genomic analyses of *Posidonia australis* seagrass meadows identifies adaptive genotypes for future-proofing. *Ecology and Evolution, 14*, e70667. https://doi.org/10.1002/ece3.70667

North Carolina Living Shorelines Academy. (2024). Last accessed: 28 May 2024. Source: https://sites.google.com/view/ncnaturalshorelinesnetwork/home

Nunez, K., Rudnicky, T., Mason, P., Tombleson, C., & Berman, M. (2022). A geospatial modeling approach to assess site suitability of living shorelines and emphasize best shoreline management practices. *Ecological Engineering, 179*, 106617. https://doi.org/10.1016/j.ecoleng.2022.106617

O'Donnell, J. (2017). Living shorelines: A review of literatures relevant to New England Coasts. *Journal of Coastal Research, 33*(2), 435–451. https://doi.org/10.2112/JCOASTRES-D-15-00184.1

O'Leary, B. C., Fonseca, C., Cornet, C. C., de Vries, M. B., Degia, A. K., Failler, P., ... & Roberts, C. M. (2023). Embracing nature-based solutions to promote resilient marine and coastal ecosystems. *Nature-Based Solutions*, *3*, 100044. https://doi.org/10.1016/j.NbSj.2022.100044

Palinkas, C. M., Orton, P., Hummel, M. A., Nardin, W., Sutton-Grier, A. E., Harris, L., Gray, M., & Williams, T. (2022). Innovations in coastline management with natural and nature-based features (NNBF): Lessons learned from three case studies. *Frontiers in Built Environment, 8*, 814180. https://doi.org/10.3389/fbuil.2022.814180

Parkinson, R. W., Juhasz, L., Xu, J., & Fu, Z. J. (2024). Future shorelines: A living shoreline site selection and design decision support tool that incorporates future conditions induced by sea level rise. *Estuaries and Coasts, 47*, 2641–2654. https://doi.org/10.1007/s12237-024-01425-9

Passeri, D. L., Bilskie, M. V., Plant, N. G., Long, J. W., & Hagen, S. C. (2018). Dynamic modeling of barrier island response to hurricane storm surge under future sea level rise. *Climatic Change*, *149*, 413–425. https://link.springer.com/article/10.1007/s10584-018-2245-8

Pausch, R. (2024). Testing strategies to enhance transplant success under stressful conditions at a tidal marsh restoration project. *Restoration Ecology, 32*(4), e14117. https://doi.org/10.1111/rec.14117

Paxton, A.B., T.N. Riley, C.L. Steenrod, B.J. Puckett, J.B. Alemu I., S.T. Paliotti, A.M. Adler, L. Exar. J.E.T. McLean, J. Kelley, Y.S. Zhang, C.S. Smith, R.K. Gittman, & B.R. Silliman. (2024). Evidence on the performance of nature-based solutions for coastal protection: Implications for researchers, practitioners, and managers from a systematic map. National Oceanic and Atmospheric Administration, National Ocean Service, National Centers for Coastal Ocean Science. NOAA NOS NCCOS Technical Memorandum 342. 28 pg. https://doi.org/10.25923/m4gf-0g84

Payne, A. R., Burdick, D. M., Moore, G. E., & Wigand, C. (2021). Short-term effects of thin-layer sand placement on salt marsh grasses: A marsh organ field experiment. *Journal of Coastal Research, 37*(4), 771–778. https://doi.org/10.2112/JCOASTRES-D-20-00072.1

Phan, K. L., Stive, M. J. F., Zijlema, M., Truong, H. S., & Aarninkhof, S. G. J. (2019). The effects of wave non-linearity on wave attenuation by vegetation. *Coastal Engineering, 147*, 63–74. https://doi.org/10.1016/j.coastaleng.2019.01.004

Piercy, C., Welp, T., & Mohan, R. (2023) Guidelines for how to approach thin-layer placement projects. Vicksburg, MS: U.S. Army Engineer Research and Development Center. https://doi.org/10.21079/11681/47724

Pillai, U. P. A., Pinardi, N., Alessandri, J., Federico, I., Causio, S., Unguendoli, S., ... & Staneva, J. (2022). A digital twin modelling framework for the assessment of seagrass nature based solutions against storm surges. *Science of the Total Environment*, *847*, 157603. https://doi.org/10.1016/j.scitotenv.2022.157603

Pittman, S. J., Stamoulis, K. A., Antonopoulou, M., Das, H. S., Shahid, M., Delevaux, J. M., ... & Mateos-Molina, D. (2022). Rapid site selection to prioritize coastal seascapes for nature-based solutions with multiple benefits. *Frontiers in Marine Science*, *9*, 832480. https://doi.org/10.3389/fmars.2022.832480

Polk, M. A., & Eulie, D. O. (2018). Effectiveness of living shorelines as an erosion control method in North Carolina. *Estuaries and Coasts*, *41*(8), 2212–2222. https://link.springer.com/article/10.1007/s12237-018-0439-y

Pontee, N. I (2022). Understanding the benefits and limitations of coastal NBS. *Coastal Engineering Proceedings.* 37. https://pdfs.semanticscholar.org/70ed/9b77b3a907786145006790e504c9aaea5958.pdf

Puchkoff, A. L., & Lawrence, B. A. (2022). Experimental sediment addition in salt-marsh management: Plant-soil carbon dynamics in southern New England. *Ecological Engineering, 175*, 106495. https://doi.org/10.1016/j.ecoleng.2021.106495

Raposa, K. B., Woolfolk, A., Endris, C. A., Fountain, M. C., Moore, G., Tyrrell, M., Swerida, R., Lerberg, S., Puckett, B. J., Ferner, M. C., Hollister, J., Burdick, D. M., Champlin, L., Krause, J. R., Haines, D., Gray, A. B., Watson, E. B., & Wasson, K. (2023). Evaluating thin-layer sediment placement as a tool for enhancing tidal marsh resilience: A coordinated experiment across eight US National Estuarine Research Reserves. *Estuaries and Coasts, 46*(3), 595–615. https://doi.org/10.1007/s12237-022-01161-y

van Rees, C. B., Hernández-Abrams, D. D., Shudtz, M., Lammers, R., Byers, J., Bledsoe, B. P., ... & Wenger, S. J. (2023). Reimagining infrastructure for a biodiverse future. *Proceedings of the National Academy of Sciences*, *120*(46), e2214334120. https://doi.org/10.1073/pnas.2214334120

Reynolds, L. K., McGlathery, K. J., & Waycott, M. (2012). Genetic diversity enhances restoration success by augmenting ecosystem services. *PLoS ONE, 7*(6), e38397. https://doi.org/10.1371/journal.pone.0038397

Ridge, J. T., Rodriguez, A. B., Joel Fodrie, F., Lindquist, N. L., Brodeur, M. C., & Coleman, S. E. (2015). Maximizing oyster-reef growth supports green infrastructure with accelerating sea-level rise. *Science and Reports, 5*(1), 14785–14788. https://doi.org/10.1038/srep14785

Rogers, K., Boon, P., Lovelock, C. E., & Saintilan, N. (2017). Coastal halophytic vegetation, p. 544–569. *In* D. A. Keith (ed.), *Australian vegetation*, 3rd ed. Cambridge Univ. Press.

Ruangpan, L., Vojinovic, Z., Plavšić, J., Doong, D. J., Bahlmann, T., Alves, A., ... & Franca, M. J. (2021). Incorporating stakeholders' preferences into a multi-criteria framework for planning large-scale nature-based solutions. *Ambio*, *50*, 1514–1531. https://doi.org/10.1007/s13280-020-01419-4

Ryan, A. B., Venuto, B. C., Subudhi, P. K., Harrison, S. A., Shadow, R. A., Fang, X., ... & Utomo, H. (2007). Identification and genetic characterization of smooth cordgrass for coastal wetland restoration. *Journal of aquatic plant management*, *45*(2), 90. https://apms.org/wp-content/uploads/japm-45-02-090.pdf

Saintilan, N., Horton, B., Törnqvist, T. E., Ashe, E. L., Khan, N. S., Schuerch, M., ... & Guntenspergen, G. (2023). Widespread retreat of coastal habitat is likely at warming levels above 1.5° C. *Nature*, *621*(7977), 112–119. https://www.nature.com/articles/s41586-023-06448-z

Sakr, A., & Altieri. (2025). Living in a material world: Support for the use of natural and alternative materials in coastal restoration and living shorelines. *Ecological Engineering*, 211. https://doi.org/10.1016/j.ecoleng.2024.107462

Saleh, F., & Weinstein, M. P. (2016). The role of nature-based infrastructure (NBI) in coastal resiliency planning: A literature review. *Journal of Environmental Management, 183*, 1088–1098. https://doi.org/10.1016/j.jenvman.2016.09.077

Saunders, M. I., Doropoulos, C., Bayraktarov, E., Babcock, R. C., Gorman, D., Eger, A. M., ... & Silliman, B. R. (2020). Bright spots in coastal marine ecosystem restoration. *Current Biology*, *30*(24), R1500-R1510. https://doi.org/10.1016/j.cub.2020.10.056

Scheld, A. M., Bilkovic, D. M., Stafford, S., Powers, K., Musick, S., & Guthrie, A. G. (2024). Valuing shoreline habitats for recreational fishing. *Ocean & Coastal Management, 253*, 107150. https://doi.org/10.1016/j.ocecoaman.2024.107150

Schoonees, T., Gijón Mancheño, A., Scheres, B., Bouma, T. J., Silva, R., Schlurmann, T., & Schüttrumpf, H. (2019). Hard structures for coastal protection, towards greener designs. *Estuaries and Coasts, 42*, 1709–1729. https://doi.org/10.1007/s12237-019-00551-z

Scyphers, S. B., Powers, S. P., Heck, K. L., Jr., & Byron, D. (2011). Oyster reefs as natural breakwaters mitigate shoreline loss and facilitate fisheries. *PLoS ONE, 6*(8), e22396. https://doi.org/10.1371/journal.pone.0022396

Scyphers, S. B., Picou, J. S., & Powers, S. P. (2015). Participatory conservation of coastal habitats: The importance of understanding homeowner decision making to mitigate cascading shoreline degradation. *Conservation Letters, 8*, 41–49. https://doi.org/10.1111/conl.12114

Scyphers, S. B., Beck, M. W., Furman, K. L., Haner, J., Keeler, A. G., Landry, C. E., ... & Grabowski, J. H. (2020). Designing effective incentives for living shorelines as a habitat conservation strategy along residential coasts. *Conservation Letters*, *13*(5), e12744. https://doi.org/10.1111/conl.12744

Seddon, N., Chausson, A., Berry, P., Girardin, C. A., Smith, A., & Turner, B. (2020a). Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B, 375*(1794), 20190120. https://doi.org/10.1098/rstb.2019.0120

Seddon, N., Daniels, E., Davis, R., Chausson, A., Harris, R., Hou-Jones, X., ... & Wicander, S. (2020). Global recognition of the importance of nature-based solutions to the impacts of climate change. *Global Sustainability*, *3*, e15. https://doi.org/10.1017/sus.2020.8

Smith, K. A., North, E. W., Shi, F., Chen, S. N., Hood, R. R., Koch, E. W., & Newell, R. I. (2009). Modeling the effects of oyster reefs and breakwaters on seagrass growth. *Estuaries and Coasts*, *32*, 748–757. https://link.springer.com/article/10.1007/s12237-009-9170-z

Smith, C. S., Gittman, R. K., Neylan, I. P., Scyphers, S. B., Morton, J. P., Fodrie, F. J., ... & Peterson, C. H. (2017). Hurricane damage along natural and hardened estuarine shorelines: Using homeowner experiences to promote nature-based coastal protection. *Marine Policy,* 81, 350–358. https://doi.org/10.1016/j.marpol.2017.04.013

Smith, C. S., Rudd, M. E., Gittman, R. K., Melvin, E. C., Patterson, V. S., Renzi, J. J., ... & Silliman, B. R. (2020). Coming to terms with living shorelines: A scoping review of novel restoration strategies for shoreline protection. *Frontiers in Marine Science*, *7*, 434. https://doi.org/10.3389/fmars.2020.00434

Staver, L. W., Morris, J. T., Cornwell, J. C., Stevenson, J. C., Nardin, W., Hensel, P., ... & Schwark, A. (2024). Elevation changes

in restored marshes at Poplar Island, Chesapeake Bay, MD: I. Trends and drivers of spatial variability. *Estuaries and Coasts*, 1–15. https://doi.org/10.1007/s12237-023-01319-2
Stewart-Sinclair, P. J., Klein, C. J., Bateman, I. J., & Lovelock, C. E. (2021). Spatial cost–benefit analysis of blue restoration and factors driving net benefits globally. *Conservation Biology, 35*(6), 1850–1860. https://doi.org/10.1111/cobi.13742
Su, J., Yin, B., Chen, L., & Gasparatos, A. (2022). Priority areas for mixed-species mangrove restoration: The suitable species in the right sites. *Environmental Research Letters*, *17*(6), 065001. https://iopscience.iop.org/article/10.1088/1748-9326/ac6b48
Suding, K. N. (2011). Toward an era of restoration in ecology: Successes, failures and opportunities ahead. *Annual Review of Ecology, Evolution, and Systematics., 42*, 465–487. https://doi.org/10.1146/annurev-ecolsys-102710-145115
Sutherland, W. J., Adams, W. M., Aronson, R. B., Aveling, R., Blackburn, T. M., Broad, S., ... & Watkinson, A. R. (2009). One hundred questions of importance to the conservation of global biological diversity. *Conservation biology*, *23*(3), 557–567. https://doi.org/10.1111/j.1523-1739.2009.01212.x
Sutton-Grier, A. E., Wowk, K., & Bamford, H. (2015). Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. *Environmental Science & Policy, 51*, 137–148. https://doi.org/10.1016/j.envsci.2015.04.006
Suykerbuyk, W., Govers, L. L., Bouma, T. J., Giesen, W. B., de Jong, D. J., van de Voort, R., ... & van Katwijk, M. M. (2016). Unpredictability in seagrass restoration: Analysing the role of positive feedback and environmental stress on Zostera noltii transplants. *Journal of Applied Ecology*, *53*(3), 774–784. https://doi.org/10.1111/1365-2664.12614
Temmerman, S., Horstman, E. M., Krauss, K. W., Mullarney, J. C., Pelckmans, I., & Schoutens, K. (2023). Marshes and mangroves as nature-based coastal storm buffers. *Annual Review of Marine Science, 15*(1), 95–118. https://doi.org/10.1146/annurev-marine-040422-092951
Thiagarajah, J., Wong, S. K., Richards, D. R., & Friess, D. A. (2015). Historical and contemporary cultural ecosystem service values in the rapidly urbanizing city state of Singapore. *Ambio, 44*, 666–677. https://doi.org/10.1007/s13280-015-0647-7
Toft, J. D., Dethier, M. N., Howe, E. R., Buckner, E. V., & Cordell, J. R. (2021). Effectiveness of living shorelines in the Salish Sea. *Ecological Engineering, 167*, 106255. https://doi.org/10.1016/j.ecoleng.2021.106255
Toft, J. D., Accola, K. L., Des Roches, S., Kobelt, J. N., Faulkner, H. S., Morgan, J. R., ... & Dethier, M. N. (2023). Coastal landforms and fetch influence shoreline restoration effectiveness. *Frontiers in Marine Science*, *10*, 1199749. https://doi.org/10.3389/fmars.2023.1199749
Tomscha, S. A., & Gergel, S.E. (2016). Ecosystem service trade-offs and synergies misunderstood without landscape history. *Ecology and Society*, 21. https://doi.org/10.5751/ES-08345-210143
Tomscha, S. A., Sutherland, I. J., Renard, D., Gergel, S. E., Rhemtulla, J. M., Bennett, E. M., ... & Clark, E. E. (2016). A guide to historical data sets for reconstructing ecosystem service change over time. *BioScience*, *66*(9), 747–762. https://doi.org/10.1093/biosci/biw086
United Nations Environment Agency. (2019). Resolution 73/284: United Nations Decade on Ecosystem Restoration (2021–2030). https://undocs.org/A/RES/73/284
van der Meulen, F., Ijeff, S., & van Zetten, R. (2023). Nature-based solutions for coastal adaptation management, concepts and scope, an overview. *Nordic Journal of Botany, 2023*(1), e03290. https://doi.org/10.1111/njb.03290
Vanderklift, M. A., Doropoulos, C., Gorman, D., Leal, I., Minne, A. J., Statton, J., ... & Wernberg, T. (2020). Using propagules to restore coastal marine ecosystems. *Frontiers in Marine Science*, *7*, 724. https://doi.org/10.3389/fmars.2020.00724
van Zelst, V. T., Dijkstra, J. T., van Wesenbeeck, B. K., Eilander, D., Morris, E. P., Winsemius, H. C., ... & de Vries, M. B. (2021). Cutting the costs of coastal protection by integrating vegetation in flood defences. *Nature communications*, *12*(1), 6533. https://www.nature.com/articles/s41467-021-26887-4
Wang, N., Chen, Q., Hu, K., Xu, K., Bentley, S. J., & Wang, J. (2023). Morphodynamic modeling of Fourleague Bay in Mississippi River Delta: Sediment fluxes across river-estuary-wetland boundaries. *Coastal Engineering, 186*, 104399. https://doi.org/10.1016/j.coastaleng.2023.104399
Waterfront Alliance. (2024). Waterfront Edge Design Guidelines. Last accessed: 28 May 2024. Source: https://wedg.waterfrontalliance.org/
Wellman, E. H., Baillie, C. J., Puckett, B. J., Donaher, S. E., Trackenberg, S. N., & Gittman, R. K. (2021). Reef design and site hydrodynamics mediate oyster restoration and marsh stabilization outcomes. *Ecological Applications, 32*, 14. https://doi.org/10.1002/eap.2506
White, C., Collier, M. J., & Stout, J. C. (2021). Using ecosystem services to measure the degree to which a solution is nature-based. *Ecosystem Services, 50*, 101330. https://doi.org/10.1016/j.ecoser.2021.101330
Wielgus, J., Grasso, M., Colgan, C., Zhuang, J., Siegel, S. C., Conran, J., & Wodajo, T. (2023). *Natural Capital Considerations for an Extension of the US Marine Economy Satellite Account* (No. w31108). National Bureau of Economic Research.
Williams, S. L., & Grosholz, E. D. (2008). The invasive species challenge in estuarine and coastal environments: Marrying management and science. *Estuaries and Coasts*, 31, 3–20. https://link.springer.com/article/10.1007/s12237-007-9031-6
Winterwerp, J. C., Albers, T., Anthony, E. J., Friess, D. A., Mancheño, A. G., Moseley, K., ... & Van Wesenbeeck, B. K. (2020). Managing erosion of mangrove-mud coasts with permeable dams–lessons learned. *Ecological Engineering*, *158*, 106078. https://doi.org/10.1016/j.ecoleng.2020.106078
Worthington, T., & Spalding, M. (2018). Mangrove restoration potential: A global map highlighting a critical opportunity. Apollo - University of Cambridge Repository. https://doi.org/10.17863/CAM.39153
Yando, E. S., Sloey, T. M., Dahdouh-Guebas, F., Rogers, K., Abuchahla, G. M., Cannicci, S., ... & Friess, D. A. (2021). Conceptualizing ecosystem degradation using mangrove forests as a model system. *Biological Conservation*, *263*, 109355. https://doi.org/10.1016/j.biocon.2021.109355
Yando, E. S., Jones, S. F., James, W. R., Colombano, D. D., Montemayor, D. I., Nolte, S., ... & Sergienko, L. (2023). An integrative salt marsh conceptual framework for global comparisons. *Limnology and Oceanography Letters*, *8*(6), 830–849. https://doi.org/10.1002/lol2.10346
Yasmeen, A., Pumijumnong, N., Arunrat, N., Punwong, P., Sereenonchai, S., & Chareonwong, U. (2024). Nature-based solutions for coastal erosion protection in a changing climate: A cutting-edge analysis of contexts and prospects of the muddy coasts. *Estuarine, Coastal and Shelf Science, 298*, 1086321. https://doi.org/10.1016/j.ecss.2024.108632
Ying, L. S., Ledet, J., Griffin, K., Loke, L. H., Bhatia, N., & Todd, P. A. (2024). Public perception of coastal eco-engineering interventions in Singapore. *Bulletin of Marine Science*. https://doi.org/10.5343/bms.2023.0087
Young, A., Runting, R. K., Kujala, H., Konlechner, T. M., Strain, E. M., & Morris, R. L. (2023). Identifying opportunities for living shorelines using a multi-criteria suitability analysis. *Regional Studies in Marine Science, 61*, 102857. https://doi.org/10.1016/j.rsma.2023.102857
Zhu, L., Chen, Q., Wang, H., Wang, N., Hu, K., Capurso, W., ... & Snedden, G. (2023). Modeling surface wave dynamics in upper Delaware Bay with living shorelines. *Ocean Engineering*, *284*, 115207. https://doi.org/10.1016/j.oceaneng.2023.115207

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