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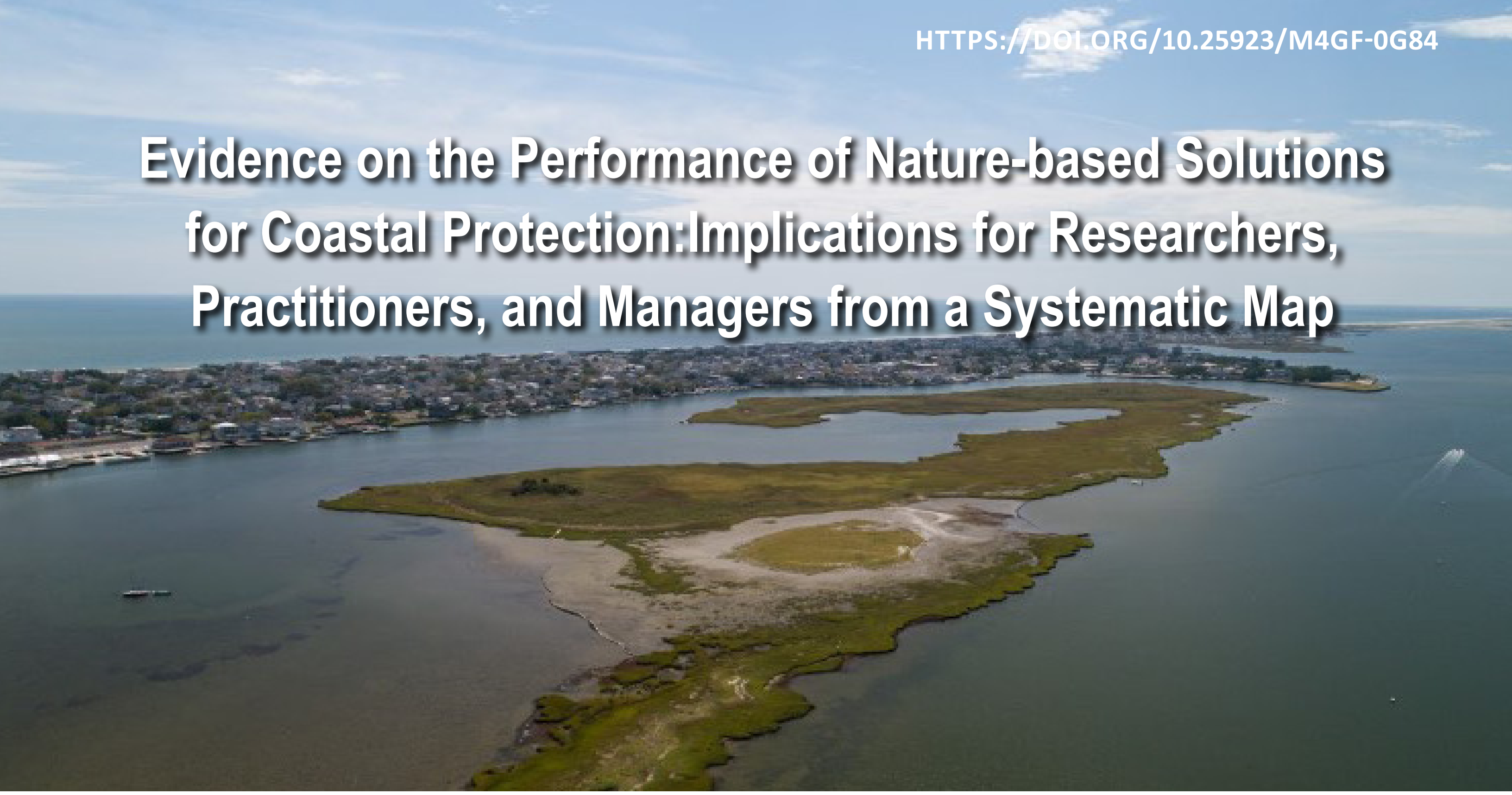

# Evidence on the Performance of Nature-based Solutions for Coastal Protection:Implications for Researchers, Practitioners, and Managers from a Systematic Map



Avery B. Paxton, Trevor N. Riley, Camille L. Steenrod, Brandon J. Puckett, Jahson B. Alemu I., Savannah T. Paliotti, Alyssa M. Adler, Laura Exar, Josette E. T. McLean, James Kelley, Y. Stacy Zhang, Carter S. Smith, Rachel K. Gittman, Brian R. Silliman

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**Cover Photo Credit:** Top left: Aerial image of restoration using dredged sediments in New Jersey (Credit: NOAA). Bottom left: Aerial image of a living shoreline off Mississippi, USA (Credit: NOAA). Bottom center: Seagrass image (Credit: NOAA). Bottom right: Coral image (Credit: NOAA).

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# Evidence on the Performance of Nature-based Solutions for Coastal Protection:Implications for Researchers, Practitioners, and Managers from a Systematic Map

Authors:
Avery B. Paxton[1]*, Trevor N. Riley[2], Camille L. Steenrod[3,1], Brandon J. Puckett[1], Jahson B. Alemu I. [4], Savannah T. Paliotti[5], Alyssa M. Adler[6], Laura Exar[6], Josette E. T. McLean[6], James Kelley[3], Y. Stacy Zhang[5], Carter S. Smith[6], Rachel K. Gittman[7,8], Brian R. Silliman[6]

[1] National Centers for Coastal Ocean Science, National Ocean Service, National Oceanic and Atmospheric Administration, 101 Pivers Island Road, Beaufort, NC
[2] Central Library, Office of Science Support, Oceanic and Atmospheric Research, National Oceanic and Atmospheric Administration, 1315 East-West Highway, Silver Spring, MD
[3] CSS Inc., 10301 Democracy Lane, Suite 300, Fairfax, VA
[4] Stokes School of Marine and Environmental Sciences, University of South Alabama, Mobile, AL
[5] Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, 2800 Faucette Drive, Raleigh, NC
[6] Duke University Marine Lab, 135 Marine Lab Road, Beaufort, NC
[7] Department of Biology, East Carolina University, 101 East 10th Street Greenville, NC
[8] Coastal Studies Institute, East Carolina University, Wanchese, NC

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| United States Department of Commerce | National Oceanic and Atmospheric Administration | National Ocean Service |
| Gina M. Raimondo<br>Secretary | Rick Spinrad, PhD<br>Under Secretary | Nicole LeBoeuf<br>Assistant Administrator |

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## Abstract

Combined impacts from anthropogenic pressures and climate change threaten the capacity of coastal ecosystems to protect communities from hazards. One approach towards improving coastal protection is to implement “nature-based solutions” (NBS), which are actions working with nature to benefit nature and humans. Despite recent increases in global implementation of NBS projects for coastal protection, substantial gaps exist in our understanding of NBS performance. To help fill this gap, we used a synthesis method called “systematic mapping” to catalog the global evidence base on the ecological, physical, economic, and social performance of NBS interventions related to coastal protection. We focused on active NBS interventions, such as restoring or creating habitat, adding structure, or modifying sediment in six shallow biogenic ecosystems: salt marsh, seagrass, kelp, mangrove, coral reef, and shellfish reef. Whereas we report highly detailed methods and accompanying findings from the systematic map in the peer-reviewed literature, here we focus on how the systematic map findings can be used by researchers, practitioners, and managers. Over 37,000 potentially relevant articles from 1980 to the 2020s were reviewed for this state-of-the-science synthesis, of which 252 were included. The compiled systematic map highlights evidence clusters related to ecological outcomes (e.g., population and species, community, habitat), physical outcomes (e.g., sediment and morphology, waves), ecosystem types (e.g., salt marsh, mangrove), and particular types of NBS interventions (e.g., restoring and enhancing systems, adding hybrid and artificial structures). These evidence clusters lie in stark contrast to nearly pervasive evidence gaps related to most economic and social performance outcomes, select ecological (e.g., ecosystem health, spatial functions and processes) and physical outcomes (e.g., storm surge, wind), some ecosystem types (e.g., seagrass, kelp), as well as for some types of NBS interventions, like altering invasive species or morphology. These findings on evidence clusters and gaps are a tool that can help guide future research, policy, and management related to NBS for coastal protection so that these interventions can be best designed, sited, constructed, monitored, and adaptively managed to maximize co-benefits.

## Keywords

Coastal protection; coastal resilience; evidence synthesis; living shoreline; natural and nature-based feature; natural infrastructure; nature-based infrastructure; restoration; systematic map

# 1. Background

To improve coastal protection, resource managers, governments, local municipalities, tribal nations, military installations, non-governmental organizations, and private property owners are increasingly turning to nature-based solutions. Nature-based solutions (NBS) are broadly defined as "actions to protect, conserve, restore, and sustainably use and manage natural or modified terrestrial, freshwater, coastal, and marine ecosystems to address social, economic, and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience, and biodiversity benefits" (UNEP 2022). Phrased more concisely, NBS are "actions that involve people working with nature, as part of nature, to address societal challenges, providing benefits for both human well-being and biodiversity" (Seddon 2022). NBS is an umbrella term (Nature 2017) that includes measures like green infrastructure, natural and nature-based features (Bridges et al. 2021), nature-based infrastructure (Sutton-Grier et al. 2018), natural infrastructure (Feagin et al. 2021), nature-climate solutions (Griscom et al. 2017), and ecosystem-based adaptation (Colls et al. 2009). *Here, we focus on the subset of active NBS interventions used to improve coastal resilience to hazards by providing physical protective services, such as wave attenuation, flood reduction, and sediment stabilization.*

Active nature-based solutions for coastal protection can come in a variety of forms and may include the creation or restoration of a variety of ecosystems with or without the inclusion of engineered structural components. The common factor among the NBS techniques we have included is the goal of providing some kind of physical protective service, such as reduced erosion and inundation, while also providing ecological co-benefits. Ecological co-benefits include, but are not limited to: increased biodiversity, improved water quality, and habitat enhancement, as well as the ability to adapt to and keep pace with stressors like sea level rise, that "gray" infrastructure (e.g., seawalls, bulkheads) either do not provide or exacerbate (e.g., coastal squeeze) (Bridges et al. 2015, Sutton-Grier et al. 2018, Bridges et al. 2021). Additional social benefits of NBS projects may include increased tourism (Leeds 2016), improvements in the aesthetic value of coastal habitats, and expanded access to cultural activities through environmental programs (Cook and Bishop 2016). Economically, NBS often provide more cost-effective solutions for inundation protection, as they can eliminate typical maintenance costs and responsibilities associated with "gray" infrastructure (Tinch and Ledoux 2006, Smith et al. 2017, Feagin et al. 2021), effectively preventing billions of dollars in flood-associated losses and repairs (Reguero et al. 2018). Although the economic and social benefits of NBS are often less thoroughly assessed than ecological benefits (Smith et al. 2020), primarily due to limited socio-economic data availability and difficulties in data collection (Ommer et al. 2022), understanding the suite of benefits NBS provide can help coastal managers and decision-makers recognize the full potential of NBS projects for coastal protection (Tinch and Ledoux 2006).

Growing evidence that NBS can provide coastal protection (physical benefits) and other valuable ecological, economic, and social co-benefits if strategically designed, placed, constructed, and managed has spurred international efforts to broadly adopt NBS for protecting coastal communities and investments from threats of climate change and associated hazards (IUCN 2016, 2020a, b, UN and IUCN 2021). The United Nations and International Union for Conservation of Nature (IUCN), heralding the 2020s as the "Decade on Ecosystem Restoration," called for approaches to reduce ecosystem degradation, one of which was nature-based solutions (UNEP and IUCN 2021). In the United States (US), this call has been met with landmark federal funding initiatives to boost the widespread use of NBS. Most recently, the US Infrastructure Investment and Jobs Act (IIJA, November 2021) allocated

$47 billion for climate resilience projects, including billions of dollars for NBS to fortify coastal communities and improve resilience (H.R.3684 2021, White House Coastal Resilience Interagency Working Group 2022, White House Council on Environmental Quality et al. 2022). In Europe, the European Commission (EC) has also allocated funding to advance the development of NBS, including in coastal settings, and mainstream it internationally through the Horizon Europe research program (previously Horizon 2020) (European Commission 2015, 2022b, a). Some European countries also have their own national plans for NBS research and development. In Germany, the Climate and Transformation Fund will supply EU €4 billion until 2026, with the goal of improving ecosystem health and resilience (Federal Ministry for the Environment et al.). NBS funding and initiatives are also prevalent in Latin American and Caribbean countries, including Mexico and Colombia (Ozment et al. 2021) and Asian countries, including China (Chinese Ministry of Ecology and Environment et al. 2022) and Japan (The Government of Japan 2022).

Despite recent increases in global implementation of NBS projects for coastal protection, substantial gaps in our understanding of NBS performance exist both broadly (Seddon et al. 2020) and relative to coastal protection (Ruangpan et al. 2020). These gaps proliferate due to a lack of studies on the broader effectiveness of NBS, especially in coastal areas; a recent review of NBS effectiveness found that only 13% of studies were conducted in coastal ecosystems, including coral reefs, mangroves, seagrass communities, and salt marshes (Chausson et al. 2020). Most NBS studies do not report on the full suite of NBS performance outcomes (Chausson et al. 2020) because it is challenging to develop, as well as costly to measure, appropriate social and ecological, as well as physical and economic performance standards (Chausson et al. 2020, Ruangpan et al. 2020, Seddon et al. 2020). For example, measuring cost-effectiveness of NBS is difficult because the protection NBS affords depends on a variety of factors, such as the intensity and frequency of events an area experiences (Seddon et al. 2020) or the time horizon over which costs are considered (Feagin et al. 2021). This is also the case, however, for gray infrastructure, but a key difference between NBS and gray infrastructure is that NBS protective services are hypothesized to increase over time, while gray infrastructure protective services may decline (Feagin et al. 2021). NBS assessments are also challenging because performance is strongly influenced by the detailed and often unique place-based context of each project (e.g., geomorphology) (Chausson et al. 2020); this is also true of gray infrastructure, but many modeling tools and design standards exist to help engineers design structures for specific levels of protection. Many NBS projects do not include budgets or requirements for monitoring, especially long-term monitoring, to ensure that projects meet expectations (Gittman et al. 2014, Kumar et al. 2021, O'Leary et al. 2023), reinforcing knowledge gaps. Inability to address these gaps in the near future will likely hinder further investment and implementation of NBS (Chausson et al. 2020), including NBS for coastal protection.

Surges in funding and subsequent construction of NBS for coastal protection, combined with the lack of NBS performance knowledge across geographies and conditions, have escalated the need to assess the performance of NBS for coastal protection. This study aimed to identify, collate, and map the global evidence base (e.g., information base, state of the science) on the ecological, physical, social, and economic performance of active NBS interventions used within the context of coastal protection in six biogenic, shallow (intertidal or subtidal) coastal ecosystems that face a variety of stressors and are among the most imperiled ecosystems on earth (Gittman et al. 2016) (Halpern et al. 2007). We used a synthesis approach called "systematic mapping," which is a gold standard among evidence synthesis techniques for summarizing the distribution and abundance of existing evidence (McKinnon 2015). The synthesis was designed to highlight the current knowledge on NBS performance in shallow, biogenic coastal ecosystems to determine the breadth and depth of the knowledge base to help inform future approaches for NBS performance assessment and management. Whereas we reported highly detailed methods and accompanying findings from the systematic map in the peer-reviewed literature (Paxton et al. 2024), our goal with this report is to identify how the systematic map findings can be used by and to inform NBS initiatives of researchers, practitioners, policy makers, and managers.

## 2. Synthesis scope

The primary research question for the systematic map was:

*What is the amount and distribution of evidence on the ecological, physical, social, and economic performance of active NBS interventions used in salt marsh, seagrass, kelp, mangrove, coral reef, and shellfish reef systems within the context of coastal protection?*

The elements of the primary question are:

•Population: Salt marsh, seagrass, kelp, mangrove, shellfish reef, or coral reef ecosystems where active NBS interventions are used.

•Intervention: Active NBS interventions established within the context of coastal protection. We used the term "active intervention" to mean the action of intentionally using, constructing, introducing, installing, or implementing NBS. We used the term NBS to describe NBS for coastal protection rather than NBS more broadly. Coastal protection must have been identified as a stated goal or measured outcome.

•Comparator: No comparator was required beyond presence of an active NBS intervention; however, studies that contained a comparator were also included. Examples of comparators are: presence vs. absence of NBS intervention, before vs. after NBS intervention, different types of NBS interventions (e.g., living shoreline vs. beneficial use), NBS monitored over time).

•Outcome: Ecological, physical, economic, or social performance outcomes evaluated following NBS interventions in the six coastal ecosystems.

•Study type: Experimental, observational, or modeling (using in-situ data) studies with quantitative or qualitative data on NBS performance outcomes

## 3. Systematic mapping

### 3.1.Technical details

The systematic map adhered to the Collaboration of Environmental Evidence (CEE) Evidence Guidelines and Standards for Evidence Synthesis (Collaboration for Environmental Evidence 2022) and conformed to the RepOrting standards for Systematic Evidence Synthesis (ROSES) (Haddaway et al. 2018). As part of this process, we developed and published a protocol or "recipe" for systematic mapping in the peer-reviewed journal *Environmental Evidence* (Paxton et al. 2023). The full systematic map findings are also published in *Environmental Evidence* (Paxton et al. 2024). Because the details of the search are provided in these two peer-reviewed publications, here we provide a summa-ry of the systematic map methods (Figure 1).

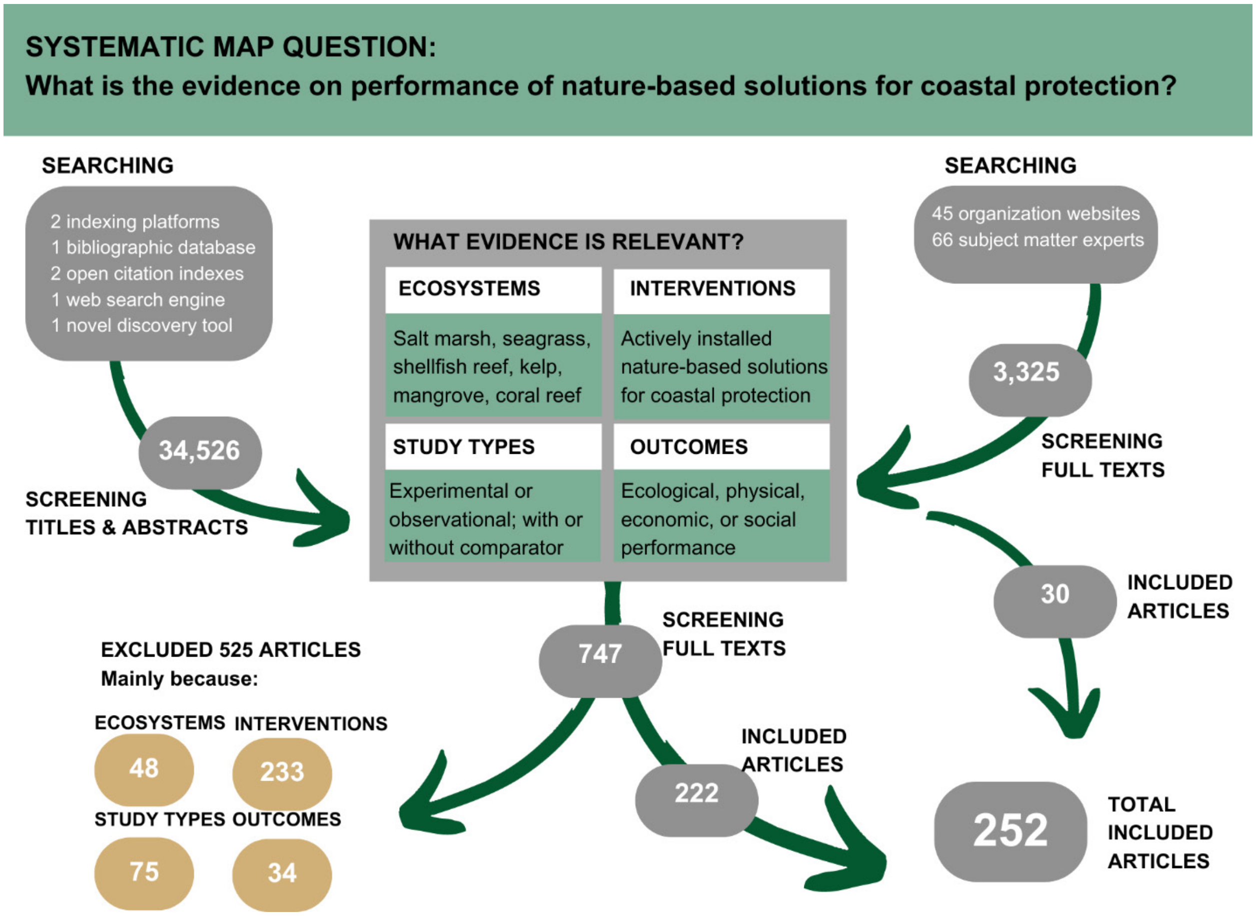


**Figure 1:** Conceptual diagram of systematic mapping approach for identifying, collating, and synthesizing existing evidence on NBS performance for coastal protection. Diagram based on conceptual diagram from S. Cheng (personal communication).

## 3.2. Search strategy development

We developed and tested search strategies to discover potentially relevant articles on NBS for coastal protection from 1980 through the 2020s. We created the search string to align with key elements of the synthesis question, specifically the population and interventions. The population search string targeted eligible coastal ecosystems (i.e., salt marsh, shellfish reef, coral reef, mangrove, seagrass, kelp) and also included more general terms, like estuary and vegetation, used to refer to these ecosystems (Table 1). The intervention search string was more complex because of the difficulty of searching for articles that reported on NBS intended to mitigate against coastal hazards and provide coastal protection benefits. We developed three substrings for the intervention string: 1) NBS, 2) hazards, and 3) mitigation (Table 1). Both hazards and mitigation substrings helped identify papers focused on coastal protection. We did not develop a search string for outcomes because we wanted to cast a broad net across the range of possible outcomes in ecological, physical, social, and economic categories. Web of Science Core Collection was used to develop and test the search strings. The population and intervention search strings (Table 1) were employed together in different combinations to capture particular types of articles (Table 2). Additionally, since search strings were developed with Web of Science syntax, we modified search strings for the particular search platform to meet platform-specific syntax requirements.

**Table 1:** Search substrings created for population and interventions. Substrings are in Web of Science Syntax, where "TI" indicates title and "AB" indicates abstract.

| PIO criteria | Concept | Substring (Web of Science syntax) |
|---|---|---|
| Population | Coastal ecosystems | (TI=(oyster* OR mussel* OR bivalve* OR shell* OR cultch* OR coral* OR reef* OR marsh* OR saltmarsh* OR wetland* OR estuar* OR kelp OR seaweed* OR seagrass* OR "sea grass*" OR mangrove* OR swamp* OR mangal* OR "aquatic plant*" OR vegetation)<br><br>OR AB= (oyster* OR mussel* OR bivalve* OR shell* OR cultch* OR coral* OR reef* OR marsh* OR saltmarsh* OR wetland* OR estuar* OR kelp OR seaweed* OR seagrass* OR "sea grass*" OR mangrove* OR swamp* OR mangal* OR "aquatic plant*" OR vegetation)) |
| Intervention | NBS | (TI=("nature based solution*" OR "nature based strateg*" OR "nature based defen$e*" OR "nature based protection*" OR "nature based coastal" OR "nature based shoreline*" OR "nature based mitigation" OR "nature based infrastructure" OR "hybrid infrastructure" OR "hybrid technique*" OR "natural climate solution*" OR "natural infrastructure" OR "eco* engineer*" OR "ecosystem friendly engineering" OR bioengineer* OR "blue engineering" OR "building with nature" OR "engineering with nature" OR "working with nature" OR "nature derived solution*" OR "nature based feature*" OR "nature inspired solution*" OR "nature inclusive design*" OR "nature inspired design*" OR "nature derived design*" OR "soft protection strateg*" OR "soft shoreline*" OR "coastal adaptation*" OR "ecosystem* based adaptation*" OR "ecosystem* based measure*" OR "ecosystem* based mitigation" OR "disaster risk reduction" OR "living shoreline*" OR "coastal defen$e*" OR "natural barrier*" OR bioshield* OR "coastal protection" OR "protect* coast*" OR "shoreline protection*" OR "blue infrastructure" OR "soft defen$e*" OR "shoreline defen$e*" OR "managed realignment" OR "ecosystem based disaster risk reduction" OR "coastal resilienc*" OR "shoreline resilienc*" OR "restor* ecosystem* function*") OR AB=("nature based solution*" OR "nature based strateg*" OR "nature based defen$e*" OR "nature based protection*" OR "nature based coastal" OR "nature based shoreline*" OR "nature based mitigation" OR "nature based infrastructure" OR "hybrid infrastructure" OR "hybrid technique*" OR "natural climate solution*" OR "natural infrastructure" OR "eco* engineer*" OR "ecosystem friendly engineering" OR bioengineer* OR "blue engineering" OR "building with nature" OR "engineering with nature" OR "working with nature" OR "nature derived solution*" OR "nature based feature*" OR "nature inspired solution*" OR "nature inclusive design*" OR "nature inspired design*" OR "nature derived design*" OR "soft protection strateg*" OR "soft shoreline*" OR "coastal adaptation*" OR "ecosystem* based adaptation*" OR "ecosystem* based measure*" OR "ecosystem* based mitigation" OR "disaster risk reduction" OR "living shoreline*" OR "coastal defen$e*" OR "natural barrier*" OR bioshield* OR "coastal protection" OR "protect* coast*" OR "shoreline protection*" OR "blue infrastructure" OR "soft defen$e*" OR "shoreline defen$e*" OR "managed realignment" OR "ecosystem based disaster risk reduction" OR "coastal resilienc*" OR "shoreline resilienc*" OR "restor* ecosystem* function*")) |
| Intervention | Hazards (coastal protection) | (TI=("coastal hazard*" OR "extreme weather" OR "extreme event*" OR "severe storm*" OR tsunami* OR typhoon* OR cyclon* OR hurricane* OR "tropical storm*" OR "storm surge*" OR monsoon* OR northeaster* OR nor'easter OR "sea level*" OR "high wind" OR "wave action") OR AB=("coastal hazard*" OR "extreme weather" OR "extreme event*" OR "severe storm*" OR tsunami* OR typhoon* OR cyclone* OR hurricane* OR "tropical storm*" OR "storm surge*" OR monsoon* OR northeaster* OR nor'easter OR "sea level*" OR "high wind" OR "wave action" )) AND (TI=(erosion OR erod* OR flood* OR inundat* OR "storm surge*") OR AB=(erosion OR erod* OR flood* OR inundat* OR "storm surge*")) AND (TI=(coast* OR shoreline* OR *tidal OR estuar* OR marsh*) OR AB=(coast* OR shoreline* OR intertidal OR subtidal OR tidal OR estuar* OR marsh*)) |
| Intervention | Mitigation (coastal protection) | (TI=(reduc* OR mitigat* OR protect* OR dissipat* OR dampen* OR attenuat* OR stabili$* OR trap* OR buffer* OR armour* OR armor* OR barrier* OR accret* OR adapt* OR breakwater*) OR AB=(reduc* OR mitigat* OR protect* OR dissipat* OR dampen* OR attenuat* OR stabiliz* OR trap* OR buffer* OR armour* OR armor* OR barrier* OR accret* OR adapt* OR breakwater*)) AND (TI=(hazard* OR erosion OR erod* OR flood* OR "storm surge*" OR wave* OR soil OR sediment* OR substrat* OR shoreline*) OR AB=(hazard* OR erosion OR erod* OR flood* OR "storm surge*" OR wave* OR soil OR sediment* OR substrat* OR shoreline*)) AND (TI=(coast* OR shoreline* OR *tidal OR estuar* OR marsh*) OR AB=(-coast* OR shoreline* OR intertidal OR subtidal OR tidal OR estuar* OR marsh*)) |

| | | |
|---|---|---|
| Intervention | Restoration | (TI=(construct* OR plant* OR install* OR restor* OR enhance* OR creat* OR retrofit*) OR AB=(construct* OR plant* OR install* OR restor* OR enhance* OR creat* OR retrofit*)) |

**Table 2:** Search string combinations employed to capture articles on NBS intended for coastal protection.

| String combination | Search designed for |
|---|---|
| NBS AND Population | Articles focused on NBS concepts from target coastal ecosystems |
| NBS AND Mitigation | Articles focused on NBS concepts and coastal mitigation actions that do not explicitly mention target ecosystems in title or abstract |
| NBS AND Hazards | Articles focused on NBS concepts and coastal hazards that do not explicitly mention target ecosystems in title or abstract |
| Population AND Mitigation AND Hazards | Articles focused on coastal ecosystems and hazards and mitigations that do not explicitly use NBS or related terms in title or abstract |
| Population AND Mitigation AND Restoration | Articles focused on coastal ecosystems and mitigations that do not explicitly use NBS or related terms in the title or abstract but do use terms related to habitat restoration and creation |

## 3.3. Searching the literature

Using the predefined search strategy, we then searched for relevant articles across multiple platforms: two indexing platforms, one bibliographic database, two open discovery citation indexes, one web-based search engine, and a novel literature discovery tool (Table 3). These searches returned 113,776 potentially relevant articles. Since the same articles were sometimes found on multiple search platforms, we deduplicated the discovered articles, after which there were 34,526 records remaining.

## 3.4. Screening discovered literature

We screened each of the 34,526 articles using their title and abstract to determine whether they met our inclusion criteria, such as coastal ecosystem, NBS type, coastal protection context, study type, and performance outcomes. We used a software called Swift Active Screener that uses a machine learning algorithm to help screen titles and abstracts (Howard et al. 2020). In total, we discovered 747 articles whose titles and abstracts appeared to be relevant. We excluded the other 33,779 articles, of which we manually excluded 9,928 and the machine learning helped exclude 23,851.

The 747 articles remaining after title and abstract screening were then screened again using the full text to determine if they did, in fact, meet our systematic map eligibility criteria. Of these, we found 211 articles that met our eligibility criteria and were included in the systematic map. We extracted metadata from these 211 articles into a codebook. The other articles were excluded either because we could not retrieve their full text, were duplicates, were not written in English, or were not eligible per our coastal ecosystem, NBS, coastal protection context, study type, or outcome criteria.

## 3.5. Additional searches

We also searched for articles on 45 organizational websites (Table 3) and solicited literature from 66 subject matter experts via email requests. These searches returned 3,042 and 283 candidate articles, respectively. Upon screening these articles by their full text, we included 20 from organizational websites and 10 from subject matter experts and extracted metadata from each.

## 3.6. Synthesizing the evidence

We analyzed and visualized metadata from the 252 articles to determine the distribution and abundance of evidence on NBS performance in shallow coastal ecosystems.

**Table 3**: Platforms searched for relevant literature on NBS for coastal protection. Indexing platforms, bibliographic databases, and open discovery citation indexes were searched with the highly technical search string. The novel literature discovery tool was seeded with key articles. The web-based search engine was searched using an abbreviated search string. The organizational websites were searched individually using filtered searches and keyword searches for up to the first 100 results.

| Search platform type | Search platform name | Search platform link |
|---|---|---|
| Indexing platform | Web of Science Core Collection | https://www.webofscience.com/ |
| | Scopus | https://www.scopus.com/ |
| Bibliographic database | ProQuest | https://www.proquest.com/ |
| Open discovery citation index | LENS | https://www.lens.org/ |
| | Dimensions | https://www.dimensions.ai/ |
| Novel literature discovery tool | Inciteful | https://inciteful.xyz/ |
| Web-based search engine | Google Scholar | https://scholar.google.com/ |
| Organizational website | Asian Development Bank: | https://www.adb.org/ |
| Organizational website | Australian Government Department of Climate Change, Energy, the Environment, and Water | https://www.dcceew.gov.au/ |
| Organizational website | Billion Oyster Project | https://www.billionoysterproject.org/ |
| Organizational website | Caribbean Natural Resources Institute | https://hub.canari.org/ |
| Organizational website | Climate Resilient by Nature | https://www.climateresilientbynature.com/ |
| Organizational website | ClimateLinks | https://www.climatelinks.org/ |
| Organizational website | Commonwealth Scientific and Industrial Research Organisation | https://www.csiro.au/ |

| | | |
|---|---|---|
| Organizational website | Conservation International | https://www.conservation.org/ |
| Organizational website | UK Government Foreign, Commonwealth & Development Office | https://www.gov.uk/ |
| Organizational website | USAID Development Experience Clearinghouse | https://www.usaid.gov/ |
| Organizational website | Deutsche Gesellschaft fur Internationale Zusammenarbeit | https://www.giz.de/ |
| Organizational website | Environmental and Energy Study Institute | https://www.eesi.org/ |
| Organizational website | Environmental Defense Fund | https://www.edf.org/ |
| Organizational website | European Union / Commission | https://op.europa.eu/ |
| Organizational website | Global Facility for Disaster Reduction and Recovery | https://www.gfdrr.org/ |
| Organizational website | Global Mangrove Alliance | https://www.mangrovealliance.org/ |
| Organizational website | Global Program on Nature-Based Solutions for Climate Resilience | https://naturebasedsolutions.org/ |
| Organizational website | iied Publications Library | https://www.iied.org/ |
| Organizational website | International Monetary Fund | https://www.imf.org/ |
| Organizational website | International Union for Conservation of Nature | https://www.iucn.org/ |
| Organizational website | National Fish and Wildlife Foundation | https://www.nfwf.org/ |
| Organizational website | National Oceanic and Atmospheric Administration | https://www.noaa.gov/ |
| Organizational website | National Science Foundation | https://www.nsf.gov/ |
| Organizational website | Oxford Nature Based Solutions Initiative | https://www.naturebasedsolutionsinitiative.org/ |
| Organizational website | rare | https://rare.org/ |
| Organizational website | Resources for the Future | https://www.rff.org/ |
| Organizational website | The Nature Conservancy | https://www.nature.org/ |
| Organizational website | United Nations Decade on Restoration | https://www.decadeonrestoration.org/ |
| Organizational website | United Nations Development Programme | https://www.undp.org/ |
| Organizational website | United Nations Environment Programme | https://www.unep.org/ |
| Organizational website | United Nations Environment Programme World Conservation Monitoring Center | https://resources.unep-wcmc.org/ |
| Organizational website | United States Army Corps of Engineers – Engineer Research and Development Center | https://erdc-library.erdc.dren.mil |
| Organizational website | United States Army Corps of Engineers – Engineering with Nature | https://ewn.erdc.dren.mil/ |
| Organizational website | United States Climate Resilience Toolkit | https://toolkit.climate.gov/ |
| Organizational website | United States Department of Transportation | https://www.transportation.gov/ |
| Organizational website | United States Environmental Protection Agency | https://www.epa.gov/ |
| Organizational website | United States Fish and Wildlife Service | https://www.fws.gov/ |
| Organizational website | United States Geological Survey | https://www.usgs.gov/ |
| Organizational website | University of Georgia Institute for Resilient Infrastructure Systems | https://iris.uga.edu/ |
| Organizational website | Wetlands International | https://www.wetlands.org/ |
| Organizational website | Wildlife Conservation Society | https://library.wcs.org/ |
| Organizational website | World Agroforestry Center | https://www.worldagroforestry.org/ |
| Organizational website | World Bank | https://www.worldbank.org/ |
| Organizational website | World Resources Institute | https://www.wri.org/ |
| Organizational website | World Wildlife Fund | https://www.worldwildlife.org/ |

## 4. Key Findings

In total, 252 articles (n=222 databases, n=20 from organizational websites, n=10 from stakeholder contributed literature) were included in the systematic map after full text screening. Details of these included articles, as well as those that were excluded because they did not meet eligibility criteria, can be found in the published systematic map (Paxton et al. 2024). Here, we summarize key and relevant findings from the systematic map with implications for research, policy, and management. In the descriptive information reported below, articles can appear in more than one category. For example, an article can have multiple coastal ecosystem population categories (seagrass, saltmarsh) or multiple NBS intervention types (structure addition, restoration). Thus, the total sample size can be greater than the total number of articles (n=252). In several instances, an article contained multiple case studies characterized by separate NBS projects that were not compared. If an article contained two or more eligible case studies, each case study was coded separately.

### 4.1. Evidence differed by ecosystem type

Evidence existed for all six types of shallow coastal ecosystems within the scope of the systematic map, although some ecosystem types had several orders of magnitude more evidence than others (Figure 2A). Salt marshes contained the most evidence on NBS performance (46%; n=133), followed by mangroves (25%; n=73), and shellfish reefs (20%; n=58). Seagrass (4%; n=12) and coral reefs (4%; n=12) had the same amount of evidence as each other. Kelp (<1%; n=1) had the least amount of evidence.

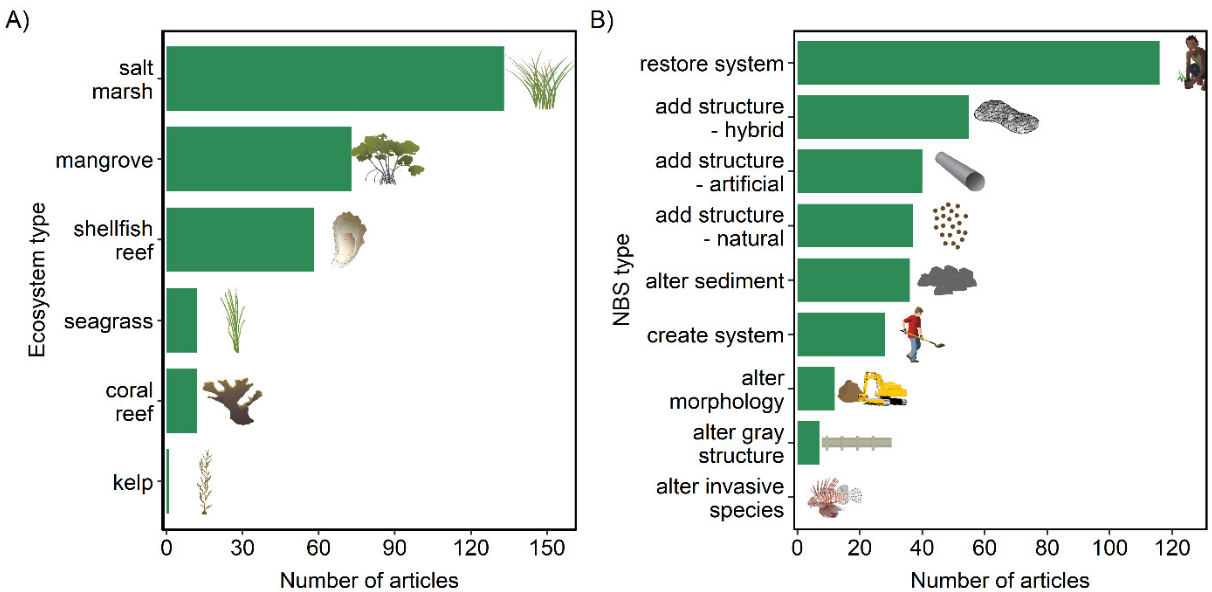


**Figure 2:** Amount of evidence (number of articles) by A) coastal ecosystem type and B) NBS type. Symbols from Integration and Application Network (ian.umces.edu/media-library).

## 4.2. Evidence differed by nature-based solutions type

Most NBS interventions were ecosystem restoration, enhancement, or rehabilitation (35%; n=116), such as salt marsh or shellfish reef restoration (Figure 2B). Other common intervention types included adding structure (40%; n=132) categorized as hybrid (17%; n=55), artificial (12%; n=40), or natural (11%; n=37) to an existing ecosystem. Hybrid structures of mixed natural and human origin ranged from bagged oysters and artificial seagrass mats to rip rap. Artificial structures encompassed reef modules like Reef Balls®, trapezoidal units, and Oyster Castles®, as well as coastal armoring structures like retrofitted seawalls. Natural structures often included rocks or sediment fences, such as those constructed from recycled Christmas trees. Other intervention types included sediment stabilization, placement, or removal (11%; n=36) through beneficial re-use or thin-layer application sediment. Other studies used ecosystem creation (9%; n=28), where a system was created in place of a naturally occurring one. Some studies also used morphology modification (4%; n=12) like installation of runnels or managed realignment. Several studies included retrofitting or removal of gray infrastructure (2%; n=7). No studies contained interventions involving modification of invasive species.

## 4.3. Multiple terms used to describe nature-based solutions

Most NBS interventions were referred to as “restoration” (n=104) or “living shorelines” (n=56; Figure 3). The term “nature-based solutions” was used in 33 cases. Other terms included “rehabilitation” (n=20), “managed realignment” (n=13), “nature-based coastal defense” (n=11), “artificial reef” (n=8), “natural infrastructure” (n=7), “natural and nature-based feature” (NNBF; n=4), “ecological engineering” (n=4), and “green engineering” (n=2). There was one instance each of the following terms: ecosystem-based adaptation, ecosystem-based disaster risk reduction, climate adaptation service, green infrastructure, and blue engineering. There were no instances with the following terms: community-based adaptation, ecosystem-based mitigation, or blue infrastructure.


**Figure 3:** Terminology used to refer to NBS. Terms within the word cloud are sized according to the amount of evidence (number of articles).

## 4.4. Evaluated ecological, physical, economic, and social outcomes

More articles examined physical outcomes (50%; n=202) and ecological outcomes (41%; n=164) than economic (5%; n=22) and social (4%; n=14) outcomes (Figure 6). The majority of evaluated ecological outcomes were related to population and species (n=78), community (n=64), and habitat (n=37; see Table 5 for example metrics). Other ecological outcomes evaluated less frequently included those related to nutrient cycling (n=18), temporal functions and processes (n=12), ecosystem productivity (n=6), and ecosystem health (n=5). Two ecological outcomes, spatial functions and processes (n=2) and biological interactions (n=2), were rarely evaluated. The most common physical outcomes were sediment and morphology (n=134) and waves (n=45). Other evaluated physical outcomes included water level (n=21) and currents (n=10). Wind (n=4) and storm surge (n=2) outcomes were rarely evaluated. Compared to ecological and physical outcomes, sparser evidence existed on economic outcomes. Few articles evaluated economic outcomes: livelihoods and employment (n=10), income (n=7), natural capital (n=4), financial capital (n=4), and tourism and recreation (n=2). Living standards was evaluated once, and physical capital was not evaluated. Social outcomes were the least evaluated outcomes compared to ecological, physical, and economic counterparts. Social outcomes included culture (n=4), education and skills (n=4), knowledge and awareness (n=4), safety and security (n=3). Rights, empowerment, and governance (n=2), as well as basic infrastructure (n=1), were rarely assessed. There was no evidence related to health or social capital.

Directionality of ecological, physical, economic, and social performance outcomes varied, encompassing positive, negative, neutral, and mixed outcome directions (Figure 4). For population or species outcomes, for example, there was a high number of cases with positive and mixed outcomes, followed by neutral and negative. Most reported physical outcomes were positive (e.g., reduced erosion rate, increased wave attenuation), yet there were examples of negative, neutral, and mixed outcomes, especially for sediment and morphology. Most reported economic outcomes were positive (e.g., reduced property damage costs), although there were several cases of mixed or neutral outcomes. Most social outcomes that were reported had positive directionality (e.g., increased educational or recreational opportunities), although safety and security also had neutral outcomes, and knowledge and awareness also had mixed outcomes.

## 4.5. Intersection of nature-based solutions types and outcomes

### 4.5.1. Nature-based solutions and ecological outcomes

Evidence clusters were most pronounced for ecological outcomes for NBS interventions that were restored ecosystems (n=94), hybrid structure addition (n=43), sediment alteration (n=33), and artificial structure addition (n=32; Figure 7). For restored systems, the highest amount of evidence stemmed from population or species (n=30) and habitat (n=21), and community (n=20) outcomes, whereas for added structures, evidence clusters occurred for population or species (n=18 hybrid; n=15 artificial) and community outcomes (n=12 hybrid; n=11 artificial). There was also a moderate amount of evidence for structure additions of natural origin for population or species outcomes (n=14). There was some evidence on temporal functions and processes, as well as nutrient cycling, especially for restoration interventions. Across all NBS interventions, there was sparse to no evidence on spatial functions, biological interactions, ecosystem health, and ecosystem productivity.

### 4.5.2. Nature-based solutions and physical outcomes

Evidence on physical performance of NBS was highest for restoration (n=82), hybrid structure addition (n=42), natural structure addition (n=34), and sediment alteration (n=33), but most of these evaluations focused on sediment and morphology, water level, or waves (Figure 6). For example, the evidence on physical performance for restored systems related to sediment and morphology (n=49), waves (n=15), and water level (n=12), and evidence on hybrid structure additions focused on sediment and morphology (n=27) and waves (n=12). There was some evidence on currents for restoration (n=3) and natural structure addition (n=3). Sparse evidence existed for wind (n=5) and storm surge (n=2) across all NBS intervention types.

### 4.5.3. Nature-based solutions and economic outcomes

Economic outcomes were assessed for restored systems (n=24), artificial structure additions (n=5), created systems (n=2), morphology alterations (n=2), hybrid structure additions (n=1), and natural structure additions (n=1; Figure 9). Within restored NBS interventions, the evidence clustered on livelihoods and employment (n=12) and income (n=8). Across most NBS intervention types and economic outcomes, there were evidence gaps. For instance, there were no economic outcomes for alteration of gray structures, sediment alteration, or alteration of invasive species.

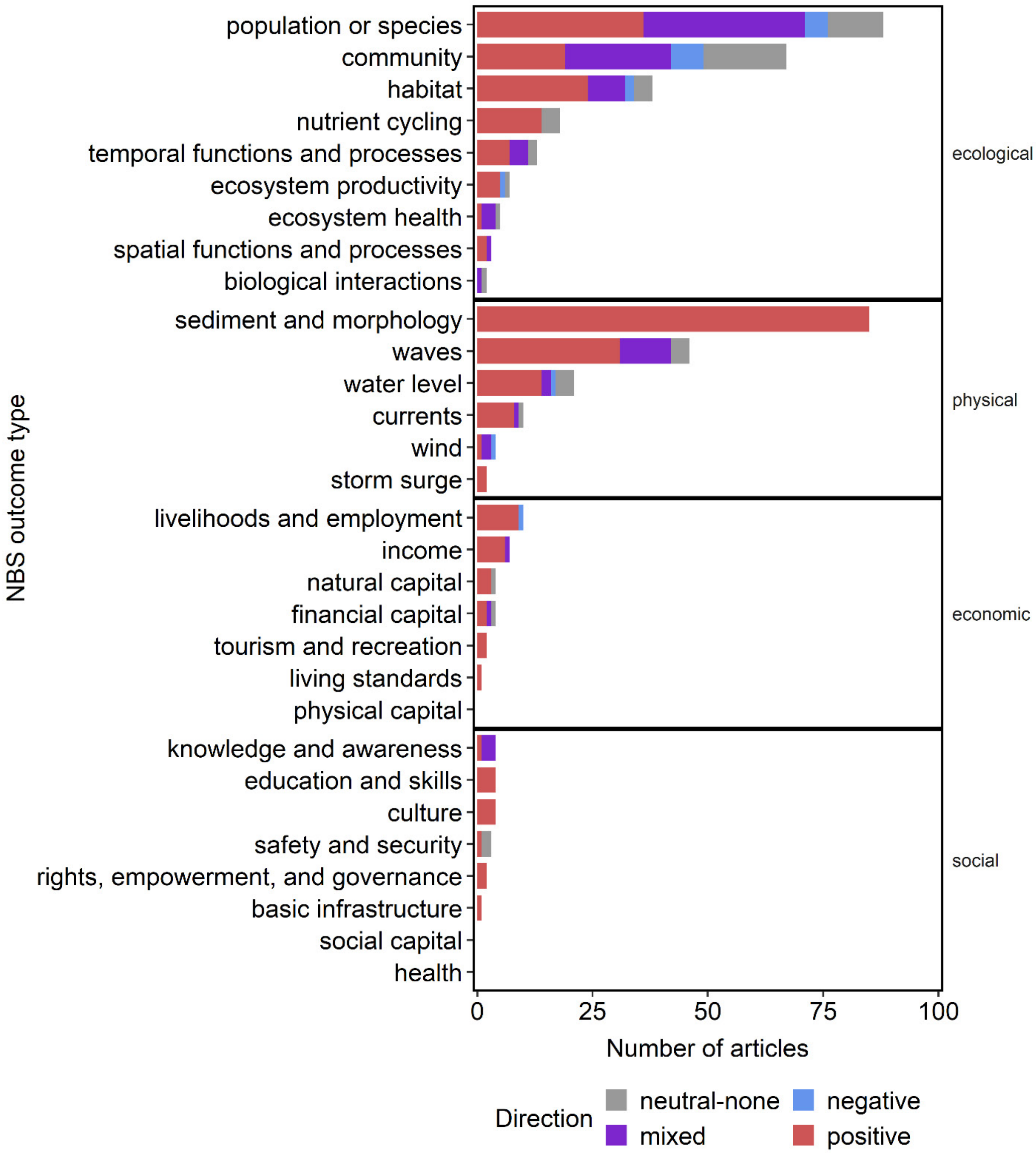


**Figure 4:** Amount of evidence (number of articles) reporting on NBS performance for A) ecological, B) physical, C) economic, and D) social outcomes. See Table S1 for examples of ecological, physical, economic, and social outcomes.

### 4.5.4. Nature-based solutions and social outcomes

Similar to economic outcomes, social outcomes were sparsely evaluated across NBS intervention types (Figure 8). Restored systems (n=13) exhibited moderate evidence related to education and skills (n=4) and culture (n=3), whereas added artificial structures had sparse evidence across multiple social outcomes. Other NBS interventions had zero to two social outcomes evaluated; no studies evaluated health or social capital.

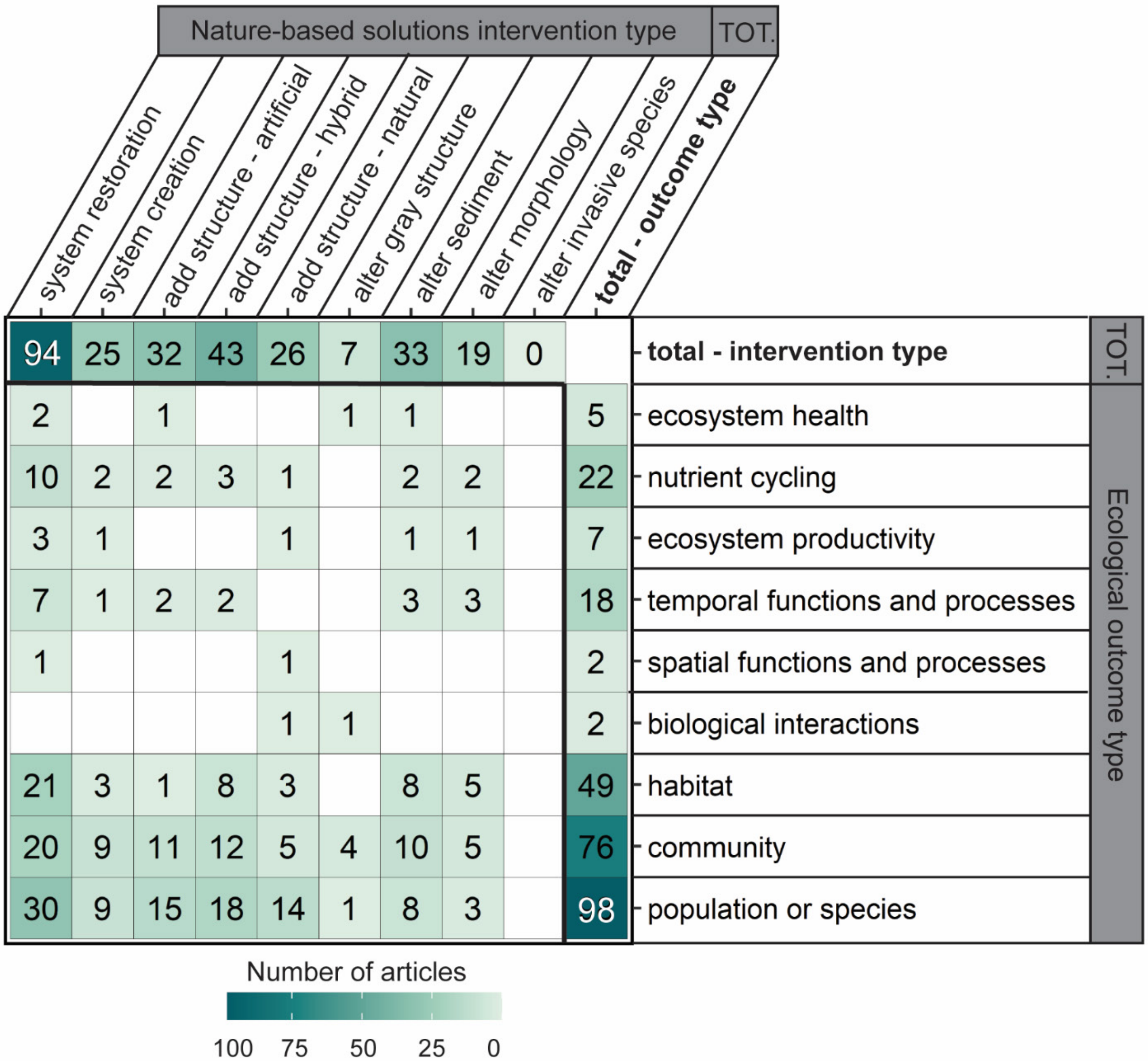


**Figure 5:** Amount of evidence (number of articles) on ecological performance of NBS for different types of NBS. Some articles contained more than one intervention or outcome so can appear in more than one cell. Blank cells have zero articles. Total values across NBS types and ecological performance outcomes are shown in the top row and far right column, respectively.

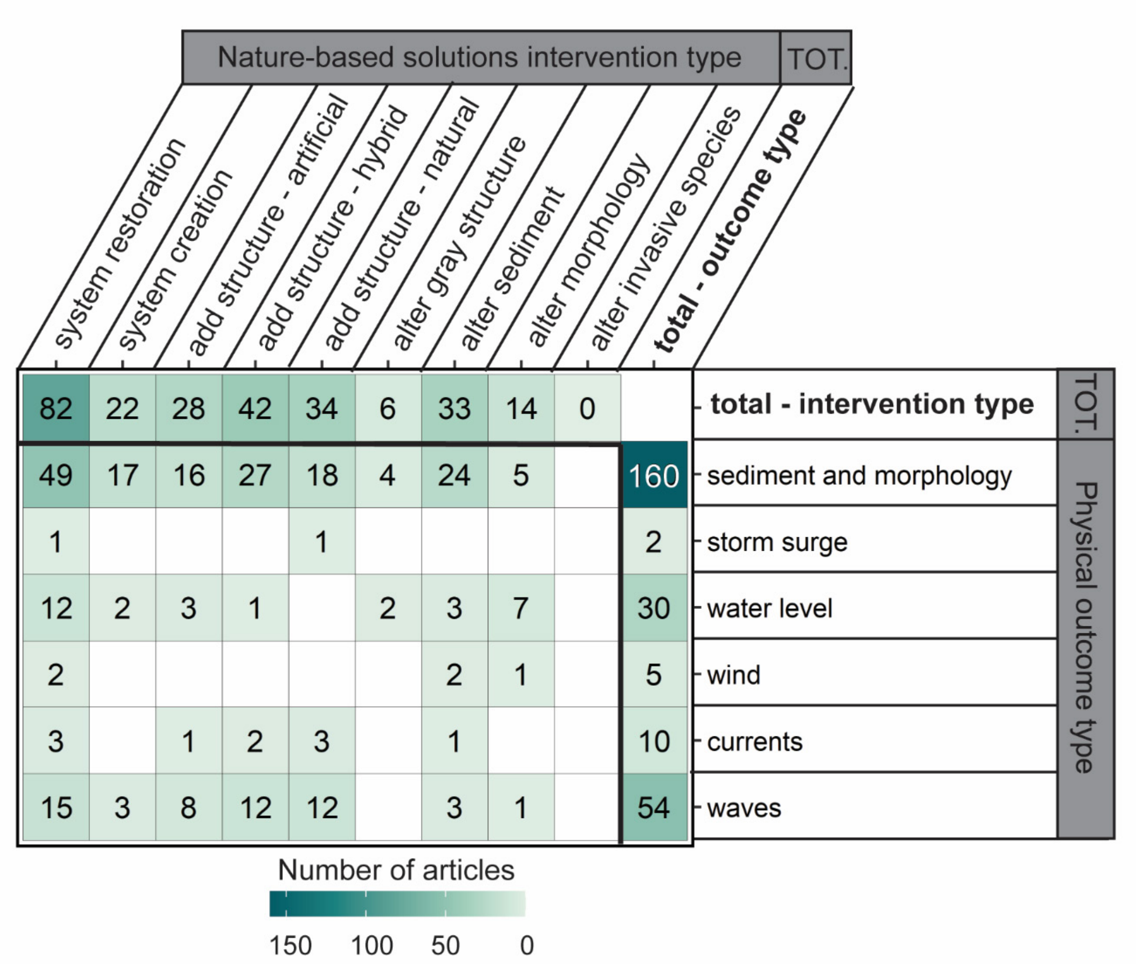


**Figure 6:** Amount of evidence (number of articles) on physical performance of NBS for different types of NBS. Some articles contained more than one intervention or outcome so can appear in more than one cell. Blank cells have zero articles. Total values across NBS types and physical performance outcomes are shown in the top row and far right column, respectively.

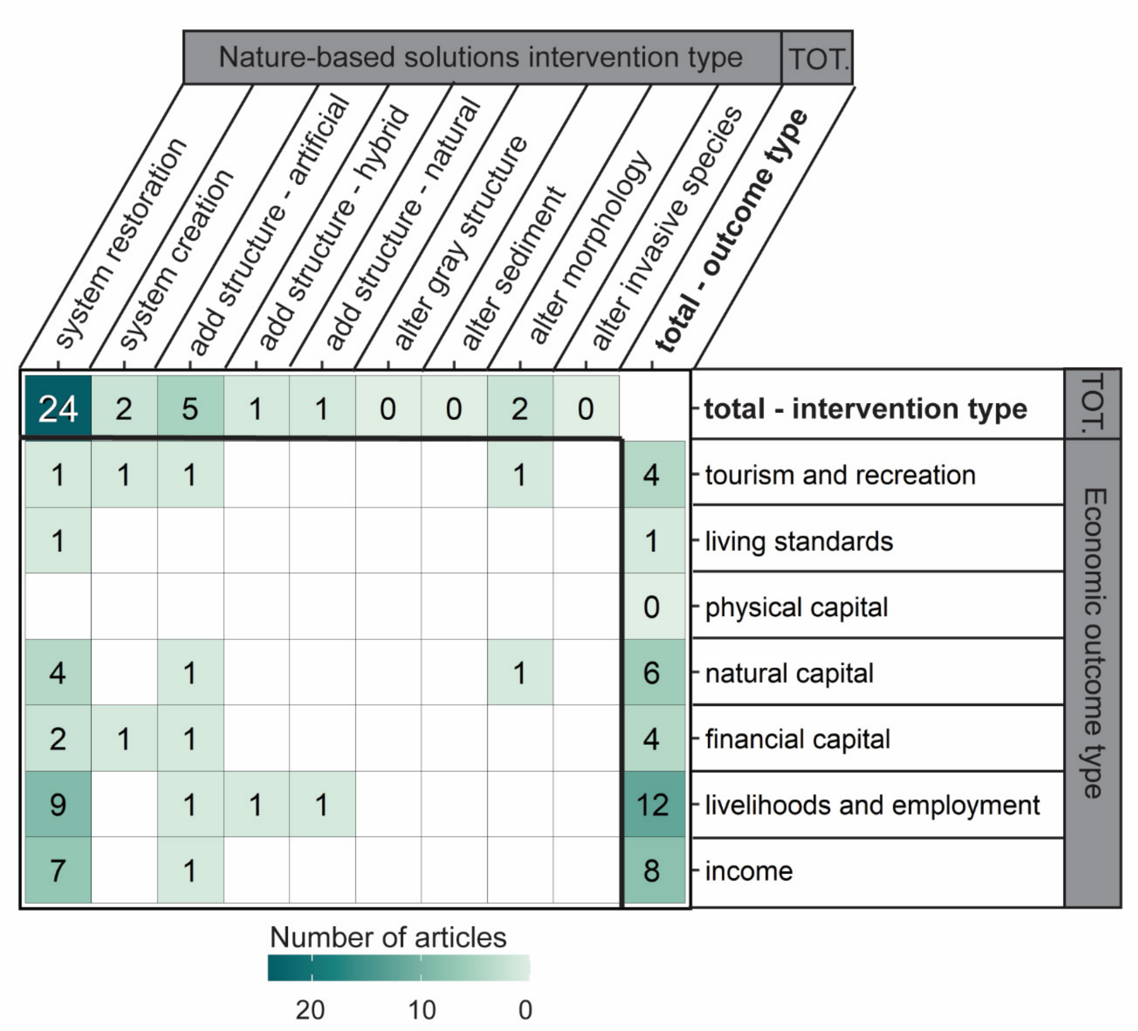


**Figure 7:** Amount of evidence (number of articles) on economic performance of NBS for different types of NBS. Some articles contained more than one intervention or outcome so can appear in more than one cell. Blank cells have zero articles. Total values across NBS types and economic performance outcomes are shown in the top row and far right column, respectively.

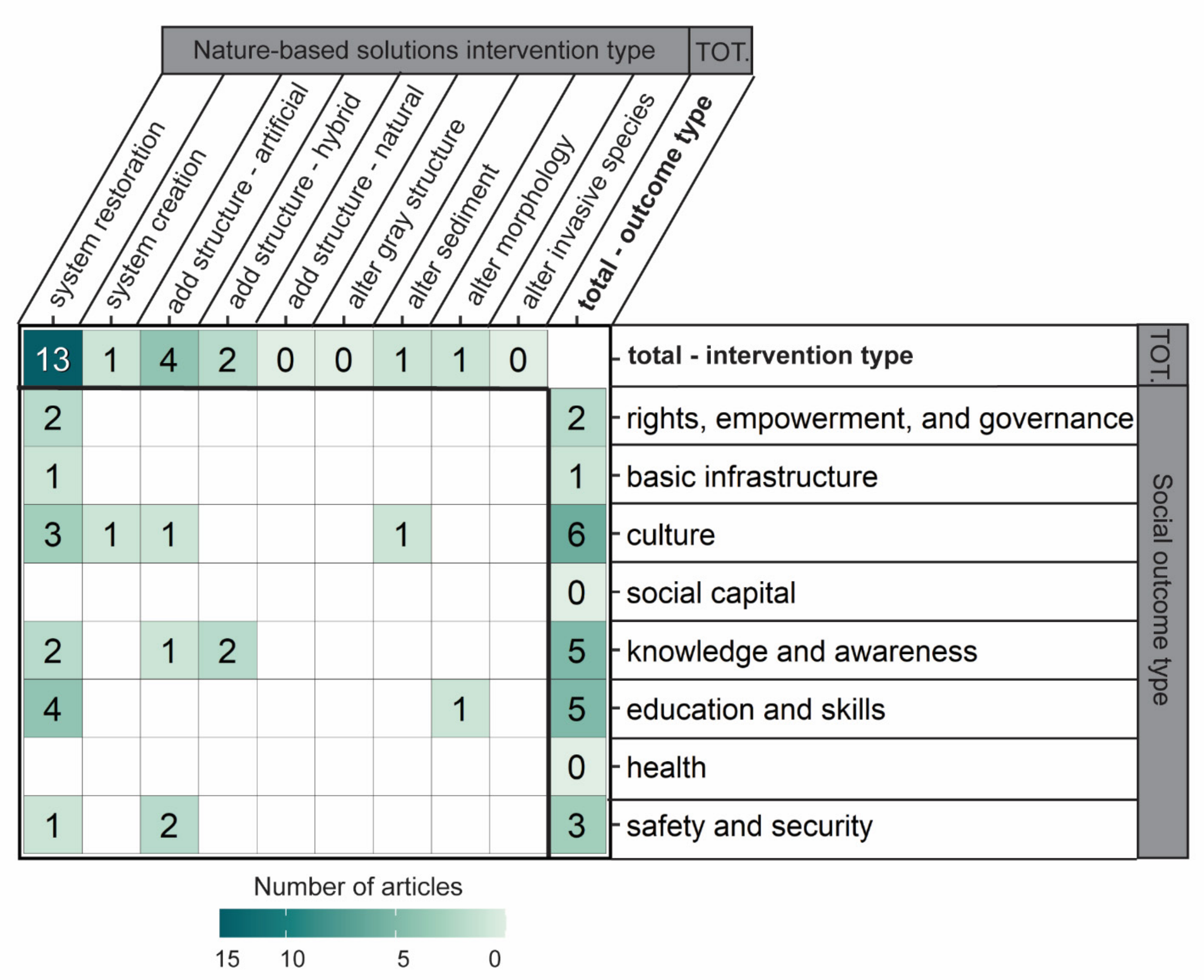


**Figure 8:** Amount of evidence (number of articles) on social performance of NBS for different types of NBS. Some articles contained more than one intervention or outcome so can appear in more than one cell. Blank cells have zero articles. Total values across NBS types and social performance outcomes are shown in the top row and far right column, respectively.

## 5. Future research directions

We suggest multiple future research directions related to NBS for coastal protection in shallow coastal ecosystems to leverage the evidence clusters and fill the evidence gaps revealed by the systematic map (Figure 9).

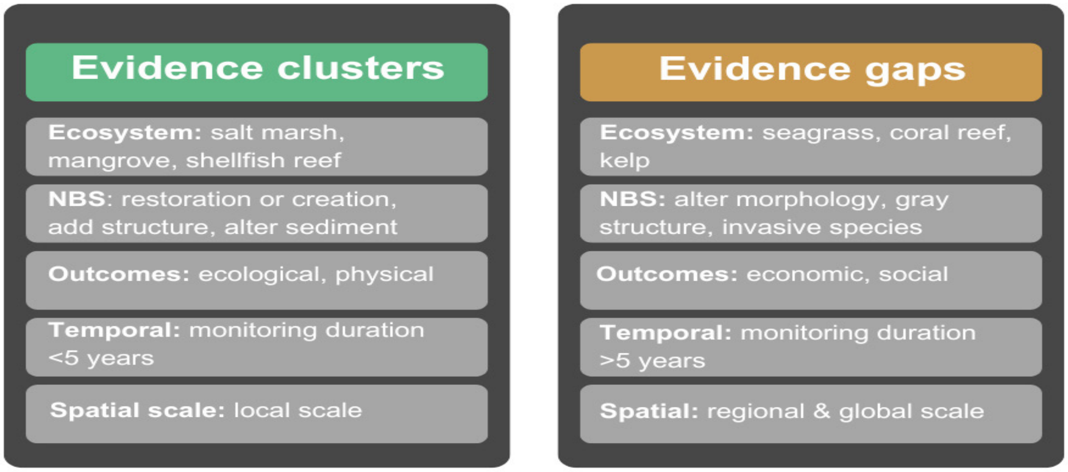


**Figure 9:** Summary of evidence clusters and knowledge gaps highlighted by the systematic map.

### 5.1. Research leveraging evidence clusters

The following are suggested research priorities that leverage existing evidence clusters:

•Conduct a systematic review using the systematic map findings to assess the magnitude and quality of evidence on NBS for coastal protection. Such a systematic review should follow standards set by the CEE.

•Evaluate effect sizes for NBS used in salt marsh, mangrove, and shellfish reef ecosystems for NBS types and outcomes of interest.

•Determine effect sizes for NBS used for restoration, enhancement, and mitigation for performance outcomes and ecosystems of interest.

•Compare the performance of NBS types characterized by added artificial structure, added hybrid structure, and added natural structures.

•Determine effect sizes for common ecological (e.g., population or species, community, habitat) and physical (e.g., sediment and morphology, waves, water level) outcomes associated with NBS.

## 5.2. Research to fill evidence gaps

The following are suggested research priorities to fill evidence gaps:

•Assess the performance of NBS in multiple ecosystems, including seagrass meadows, coral reef, and kelp forests.

•Evaluate economic and social performance outcomes associated with NBS projects as a standard practice for NBS assessments.

•Assess the performance of NBS types that include alteration of gray infrastructure, alteration of morphology, and alteration of invasive species.

•Determine the ecological performance of NBS for biological interactions, ecosystem health, ecosystem productivity, and spatial functions and processes. Nutrient cycling and temporal functions and processes are also of interest but have less extensive evidence gaps.

•Monitor the physical performance of NBS for storm surge, winds, and currents.

•Evaluate the economic performance of NBS for a variety of outcomes, including tourism and recreation, living standards, capital (physical, natural, financial), livelihoods and employment, and income.

•Assess the social performance of NBS for a variety of outcomes, including safety and security, health, education and skills, knowledge and awareness, social capital, culture, basic infrastructure, and rights, empowerment, and governance.

•Determine whether existing NBS projects have been designed, sited, implemented, and managed equitably.

•Monitor NBS projects over broad temporal (> 5 years) and spatial scales (regional, global) for ecological, physical, economic, and social performance.

•Develop best practices for monitoring NBS performance outcomes to assess both co-benefits and unintended outcomes.

## 6. Implications for practitioners

Practitioners tasked with implementing NBS projects can use the systematic map findings as a tool as follows:

•Identify NBS projects included in the systematic map and the accompanying database of studies that use similar approaches (e.g., ecosystem type, NBS type, outcome, geographic location) to projects that the practitioner plans to implement. The practitioner can review information about each similar project to learn what worked, what failed, what challenges were faced, and how information was reported.

•Convene regional workshops with the practitioner community to identify best practices for NBS implementation and monitoring, using the evidence clusters and gaps highlighted by the systematic map to inform initial workshop discussions and develop a network for future collaboration.

•Convene multidisciplinary teams to monitor a full suite of NBS performance outcomes, including ecological, physical, economic, and social.

•Develop training opportunities for community members and students focused on evaluating NBS performance for coastal protection, added co-benefits, and unintended consequences.

•Determine which monitoring methods and metrics are most suitable for assessing NBS performance.

•Develop a plan for broader temporal monitoring to generate time series of NBS performance.

## 7. Implications for policy makers and managers

Managers and policy makers can use the systematic map findings to help prioritize and guide future initiatives related to NBS for coastal protection. Suggested uses of the NBS systematic map include:

•Encourage multidisciplinary approaches for more holistically evaluating NBS performance not only ecologically and physically but also economically and socially.

•Develop initiatives to help fill knowledge gaps on NBS performance, especially relative to understudied coastal ecosystems (kelp, seagrass, coral reefs) and NBS types (invasive species modification, morphology alteration), and socioeconomic outcomes.

•Develop initiatives to produce future systematic reviews and quantitative analyses on areas of NBS performance with evidence clusters on coastal ecosystems (salt marsh, mangrove, shellfish reefs) and NBS types (restoration, structure addition, sediment alteration), and ecological and physical outcomes.

•Convene new monitoring efforts for NBS sites with historical data but no current monitoring programs to develop long-term time series and compare past performance of NBS projects to current performance.

•Create standards and guidelines or “best practices” for NBS projects. For instance, the map suggests that best practices include monitoring ecological, physical, economic, and social data so that projects designed for coastal protection can also collect sufficient data on co-benefits or unintended consequences.

•Find examples of successful or unsuccessful NBS to help guide adaptive management or adjustment of NBS strategies.

•Assess the geographic and socioeconomic distribution of NBS to determine whether NBS have been implemented equitably.

## 8. Conclusions

The systematic map details the published evidence base on the ecological, physical, economic, and social performance of NBS for coastal protection from 1980 through the early 2020s. The map reveals patterns in the distribution and abundance of evidence on NBS performance by publication traits (e.g., publication type, year, geography), ecosystem type, NBS intervention type, coastal protection context, study type characteristics (e.g., spatial scale, study design, cost reported), as well as a diverse suite of outcomes. In particular, the compiled systematic map highlights evidence clusters related to ecological outcomes (e.g., population and species, community, habitat), physical outcomes (e.g., sediment and morphology, waves), ecosystem types (salt marsh, mangrove), and particular types of NBS interventions (e.g., restoring and enhancing systems, adding hybrid and artificial structures). These evidence clusters lie in stark contrast to nearly pervasive evidence gaps related to most economic and social performance outcomes, select ecological (e.g., ecosystem health, spatial functions and processes) and physical outcomes (e.g., storm surge, wind), some ecosystem types (e.g., seagrass, kelp), as well as for some types of NBS interventions, like altering invasive species or morphology. These findings on evidence clusters and gaps can help guide future research and management of NBS for coastal protection so that these interventions can be best designed, sited, constructed, monitored, and adaptively managed to maximize co-benefits.

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**Supporting Information**

**Table S1:** Common metrics used to assess nature-based solutions performance for A) ecological, B) physical, C) economic, and D) social outcomes.

| category | subcategory | metrics |
|---|---|---|
| **A) ecological** | population or species | abundance |
| | | biomass |
| | | catch per unit effort |
| | | density |
| | | size |
| | | mortality |
| | | growth |
| | | recruitment |
| | | survival |
| | | presence / absence |
| | | biological traits |
| | | cover (individual or population) |
| | community | community composition |
| | | abundance |
| | | diversity |
| | | evenness |
| | | richness |
| | | cover (community) |
| | habitat | cover |
| | | area |
| | | presence / absence |
| | | vertical relief |
| **category** | **subcategory** | **metrics** |
| | biological interactions | species interactions |
| | spatial functions and processes | spatial distribution |
| | temporal functions and processes | colonization |
| | | succession |
| | | recruitment |
| | | resilience |
| | | growth over time |
| | | morality over time |
| | ecosystem productivity | primary production |
| | | secondary production |

**Table S1 contd:** Common metrics used to assess nature-based solutions performance for A) ecological, B) physical, C) economic, and D) social outcomes.

| | | |
|---|---|---|
| | | habitat function |
| | ecosystem health | toxin and contaminant distribution |
| | nutrient cycling | nitrogen concentration |
| | | carbon concentration |
| | | soil nutrient concentrations |
| | | denitrification |
| | | carbon sequestration |
| | | water retention |
| **B) physical** | waves | wave attenuation |
| | | wave speed |
| | | wave energy |
| | | wave height |
| | currents | current speed |
| | | current magnitude |
| | | current dissipation |
| | | turbulence |
| | winds | wind speed |
| | water level | flooding level |
| | | flood risk |
| | | water surface elevation |
| | | tidal inundation |
| | storm surge | storm surge magnitude |
| | sediment and morphology | accretion |
| | | erosion |
| | | elevation |
| | | slope |
| **category** | **subcategory** | **metrics** |
| | | depth |
| | | bulk density |
| | | sediment particle size |
| | | sediment composition |
| | | shoreline or habitat position |
| | | sediment transport or flux |
| | | sedimentation rate |
| | | sediment deposition |
| **C) economic** | income | additional income |
| | | household income |

**Table S1 contd:** Common metrics used to assess nature-based solutions performance for A) ecological, B) physical, C) economic, and D) social outcomes.

| | | |
|---|---|---|
| | | individual income |
| | livelihoods and employment | livelihood benefits |
| | | job generation |
| | | percent labor |
| | | yield / production |
| | | business ventures |
| | financial capital | costs |
| | | savings |
| | natural capital | costs from NBS and services |
| | | willingness to pay |
| | living standards | poverty rate |
| | tourism and recreation | tourism income |
| | safety and security | hazard concern |
| | | emergency response capacity |
| **D) social** | education and skills | education opportunities |
| | | technical training |
| | | student education attendance |
| | knowledge and awareness | community activities |
| | | response rates of community |
| | | individual and community perception |
| | culture | historical preservation |
| | | recreation opportunities |
| | | scenic opportunities |
| | basic infrastructure | public service benefits |
| | rights, empowerment, and governance | social empowerment |
| | | community and household resilience |

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National Ocean Service
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