From Monitoring to Accounting: Integrating Coastal Nature-based Solutions Monitoring into Natural Capital and Cost-Benefit Frameworks

Laura Costadone[1], Rakib Hassan[2] and Julia Fucci[3]

[1]Institute for Coastal Adaptation and Resilience, Old Dominion University, Norfolk, VA; [2]Department of Civil & Environmental Engineering, Old Dominion University, Norfolk, VA; [3]Chesapeake Research Consortium, Annapolis, MD

Photo credit: Laura Costadone

About the Scientific and Technical Advisory Committee

The Scientific and Technical Advisory Committee (STAC) provides scientific and technical guidance to the Chesapeake Bay Program (CBP) on measures to restore and protect the Chesapeake Bay. Since its creation in December 1984, STAC has worked to enhance scientific communication and outreach throughout the Chesapeake Bay Watershed and beyond. STAC provides scientific and technical advice in numerous ways, including (1) technical reports and papers, (2) discussion groups, (3) assistance in organizing merit reviews of CBP programs and projects, (4) technical workshops, and (5) interaction between STAC members and the CBP. Through professional and academic contacts and organizational networks of its members, STAC ensures close cooperation among and between the various research institutions and management agencies represented in the Watershed. For additional information about STAC, please visit the STAC website at www.chesapeake.org/stac.

Suggested citation: Costadone, L., R. Hassan, and J. Fucci. 2026. *From Monitoring to Accounting: Integrating Coastal Nature-based Solutions Monitoring into Natural Capital and Cost-Benefit Frameworks.* STAC Publication Number 26-008, Chesapeake Bay Program Scientific and Technical Advisory Committee (STAC), Edgewater, MD. 48 pp.

Acknowledgements

We extend our sincere gratitude to the Chesapeake Bay Program's Scientific and Technical Advisory Committee (CBP STAC) for funding and supporting this initiative. We are particularly grateful to the members of the project's advisory committee for their strategic guidance, as well as to the participants of the charrettes and Environment Virginia event, whose thoughtful feedback and diverse perspectives helped shape the project's outcomes. We also wish to acknowledge Julie Reichert-Nguyen of the National Oceanic and Atmospheric Administration (NOAA) Chesapeake Bay Office, Dr. Matthew Falcone, and the Institute for Coastal Adaptation and Resilience at Old Dominion University for their valuable contributions and institutional support. Additional thanks go to the CBP Adaptation Workgroup (formerly the Climate Resiliency Workgroup), the NOAA Oyster Team, Brooke Landry of the CBP Submerged Aquatic Vegetation Workgroup, and Kati Grigsby of the Chesapeake Bay Foundation for sharing their expertise and supporting this effort. Their collective insights and contributions have been instrumental in the development of this work.

Project Advisory Committee members:

- Katherine (KC) Filippino — Hampton Roads Planning District Commission (HRPDC)
- Kevin Du Bois — U.S. Department of Defense (DOD)
- Donna Bilkovic — Virginia Institute of Marine Science (VIMS)
- William Nardin — University of Maryland Center for Environmental Science (UMCES)
- Celso Ferreira — George Mason University (GMU)
- Siddharth Narayan — East Carolina University (ECU), Outer Banks Campus
- Katie Warnell — Duke University
- Lydia Olander — Duke University
- Ben McFarlane — Hampton Roads Planning District Commission (HRPDC)

- Jennifer (Jenny) Davis — NOAA National Centers for Coastal Ocean Science (NCCOS)
- Cindy Palinkas — University of Maryland Center for Environmental Science (UMCES)
- Donna A. Milligan — Virginia Institute of Marine Science (VIMS)
- Nicole Carlozo — Maryland Department of Natural Resources (MDNR)
- Rebecca (Becky) Swerida — Maryland Department of Natural Resources (MDNR)
- Julie Reichert-Nguyen — National Oceanic and Atmospheric Administration (NOAA)
- Mark Bennett — U.S. Geological Survey (USGS)
- Justin Shafer — City of Norfolk
- Molly Mitchell — Virginia Institute of Marine Science (VIMS)

Contents

About the Scientific and Technical Advisory Committee 2
Acknowledgements 2
Executive Summary 6
1. Introduction 9
1.1 Coastal Nature-based Solutions in the Chesapeake Bay 9
1.2 Barriers to Scaling NbS and Restoration in Coastal Practice 9
1.3 About This Framework 11
1.4 Intended Users and How to Use This Guidebook 11
2. Framework Foundations 12
2.1 Ecosystem Typology as Foundation 12
2.2 Distinguishing Nature-based Solutions from Ecological Restoration 12
2.3 From Biophysical Structure to Ecosystem Service Outcomes 13
2.4 Aligning Monitoring with Natural Capital Accounting 15
2.5 Performance Indicators and Metrics 17
3. Seagrass Meadows and Submerged Aquatic Vegetation 18
3.1 Definition and Regional Context 18
3.2 Ecosystem Services 18
3.3 Characteristics of an SAV Meadow in Good Ecological Condition 19
3.4 Restoration and Management Approaches 20
3.5 Performance Indicators and Metrics 20
4. Shellfish Beds and Oyster Reefs 23
4.1 Definition and Regional Context 23
4.2 Ecosystem Services 23
4.3 Characteristics of an Oyster Reef in Good Ecological Condition 24
4.4 Restoration and Management Approaches 25
4.5 Performance Indicators and Metrics 26
5. Coastal Saltmarshes and Reedbeds 28
5.1 Definition and Regional Context 28
5.2 Ecosystem Services 28
5.3 Characteristics of a Saltmarsh in Good Ecological Condition 29
5.4 Restoration and Management Approaches 30

5.5 Performance Indicators and Metrics 31
6. Reading the Results in Context: Scale, Landscape, and a Changing Baseline 34
7. Future Work 35
References 36
Appendix A. Literature Reviewed 43
Appendix B. Charrette Summary: Main Takeaways for Ecosystem Services, Performance Indicators, and Metrics 47

Executive Summary

Nature-based Solutions (NbS) and ecological restoration are increasingly used across the Chesapeake Bay to address interconnected challenges including coastal flooding and erosion, water-quality degradation, habitat loss, and climate change. Investments in tidal marsh restoration, oyster reefs, submerged aquatic vegetation (SAV), and living shorelines have expanded substantially, yet evaluating their long-term effectiveness remains difficult. Monitoring approaches vary across projects and jurisdictions, ecological condition is not always explicitly connected to ecosystem service delivery, and the resulting evidence can be difficult to translate into the economic and decision-making frameworks used to allocate public and private investment. These limitations constrain cross-project learning, adaptive management, and the ability to demonstrate the long-term value of investing in nature.

This guidebook provides a unified framework for evaluating whether coastal restoration and NbS interventions are recovering the ecosystem condition and functional capacity necessary to sustain intended ecosystem services and societal benefits over time. Rather than defining success by whether an intervention was constructed or implemented, the framework focuses on the ecological mechanisms through which restoration generates outcomes. It follows a causal pathway from ecosystem structure and condition → ecological function → ecosystem service → societal benefit, recognizing that sustained service delivery ultimately depends on the condition and functionality of the ecosystem itself.

Box 1. This guidebook at a glance

What it does	Future work
✓ Provides a unified set of performance indicators and scalable metrics for three Chesapeake Bay ecosystem groups: seagrass meadows and SAV, shellfish beds and oyster reefs, and coastal saltmarshes and reedbeds.	→ Quantifying and valuing ecosystem service flows to support cost-benefit comparison with grey infrastructure.
✓ Links indicators to ecological functions, ecosystem services, and NbS outcome dimensions.	→ Practical guidance on monitoring costs and effort, including literature values and proxy data.
✓ Generates standardized evidence on the state and trajectory of restored ecosystems to support SEEA EA ecosystem condition accounts.	→ Case studies applying the framework to Chesapeake Bay projects, and a detailed comparison with CBP Expert Panel crediting protocols.
✓ Offers a modular structure so practitioners can select indicators suited to their objectives and monitoring capacity.	→ Extension to additional ecosystem groups, such as sandy shorelines and coastal shrublands and grasslands.

The framework is organized around four interconnected restoration and/or NbS outcome dimensions: Coastal Hazard Risk Reduction, Climate Mitigation, Habitat Quality & Ecosystem Integrity, and Socioeconomic Benefits. Habitat Quality & Ecosystem Integrity represents the condition of the ecosystem asset itself, while the remaining dimensions capture services and benefits supported by that ecological foundation. For each outcome, the framework links ecological functions and service pathways to performance indicators and measurable metrics, allowing practitioners to select monitoring variables that are explicitly connected to the objectives of an intervention rather than collecting ecological data without a clear relationship to project performance.

The IUCN Global Ecosystem Typology (GET) provides the ecological foundation for the framework. Organizing indicators around ecosystem functional groups rather than administrative habitat categories or individual NbS types provides a consistent basis for defining ecosystem identity (which ecosystem type a site belongs to, and therefore which reference conditions apply), identifying appropriate reference conditions, and comparing ecological trajectories across sites and jurisdictions. The current guidebook applies this approach to three Chesapeake Bay ecosystem groups that are major regional restoration priorities: seagrass meadows and submerged aquatic vegetation, shellfish beds and oyster reefs, and coastal saltmarshes and reedbeds. Additional coastal ecosystem groups can be incorporated through future applications of the framework.

Performance indicators and metrics were identified through a scoping review of the scientific literature and multiple rounds of structured expert engagement, integrating measures with demonstrated ecological relevance with practitioner knowledge of their feasibility and applicability in Chesapeake Bay restoration contexts. Across ecosystem types, the framework distinguishes among environmental conditions that influence restoration trajectories, measures of ecosystem condition and structural integrity, ecological functions and service pathways, and downstream societal benefits. This distinction is critical for interpretation: environmental variables can help explain why restoration succeeds or underperforms, while condition and functional indicators provide more direct evidence of whether ecological recovery is occurring and whether the capacity for service delivery is being restored.

Application of the framework demonstrates that the specific pathways and indicators needed to evaluate performance differ among ecosystems while following a common analytical logic. For SAV, monitoring emphasizes environmental conditions supporting establishment and persistence, meadow extent and structural condition, habitat and fisheries support, carbon storage, and wave and sediment dynamics. Oyster reef monitoring similarly distinguishes environmental suitability from oyster population condition and reef structural integrity, followed by functions associated with filtration and nutrient cycling, habitat and fisheries support, and, particularly for intertidal and nearshore reefs, wave attenuation and sediment stabilization. Saltmarsh monitoring integrates vegetation and spatial condition, elevation and sediment dynamics, nutrient processing and habitat support, carbon storage and sequestration, and coastal hazard reduction. For all three ecosystems, selected pathways extend to socioeconomic outcomes such as restoration employment, fisheries and recreation activity and, where the ecosystem reduces coastal hazards, avoided damages and asset protection.

A central objective of the framework is to make restoration monitoring compatible with Natural Capital Accounting (NCA). The framework is designed to support the System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA-EA), particularly ecosystem condition accounts, by generating standardized evidence on the state and trajectory of restored ecosystem assets. With appropriate spatial attribution, aggregation, and reference conditions, monitoring data can document changes in ecosystem condition and help connect those changes to ecosystem service supply. Selected service flows can subsequently be linked to economic valuation and cost-benefit analysis, providing a pathway from field monitoring to information relevant to planning, investment, and funding decisions.

The framework is intended as decision-support guidance rather than a prescriptive monitoring protocol. Not every project needs to measure every indicator, and the appropriate combination of metrics will depend on project objectives, ecosystem type, restoration approach, spatial scale, environmental

setting, available resources, and monitoring capacity. Its modular structure allows local managers, restoration practitioners, community organizations, planners, funders, and regional agencies to select indicators appropriate to their needs while maintaining a common conceptual structure that supports comparison and aggregation across projects.

By connecting restoration action to ecosystem condition, ecological function, ecosystem services, and ultimately societal value, this guidebook provides a common foundation for evaluating coastal NbS across the Chesapeake Bay. Its broader purpose is to move restoration monitoring beyond documenting what was built or what changed immediately after implementation toward determining whether investments in nature are rebuilding ecological assets capable of sustaining benefits over the long term, and generating the evidence needed to incorporate those benefits into management, natural capital accounting, and investment decisions.

1. Introduction

1.1 Coastal Nature-based Solutions in the Chesapeake Bay

The Chesapeake Bay and its coastal areas support extraordinary ecological and human systems. The coastal region is home to nearly 10 million residents and is embedded within a watershed spanning six states and the District of Columbia, with a total population of over 19 million people. The region sustains fish, crabs, migratory waterfowl, and diverse coastal habitats alongside forested landscapes, agricultural lands, and major metropolitan areas (Turner et al., 2025; Chesapeake Bay Program, 2024; Coffin et al., 2021) (Figure 1). Yet decades of urban development and accelerating sea level rise have degraded these ecosystems, prompting large-scale, multi-jurisdictional restoration efforts, as well as numerous smaller, local-scale nature-based solutions such as living shorelines, aimed at recovering ecological function and sustaining the services coastal systems provide to society.

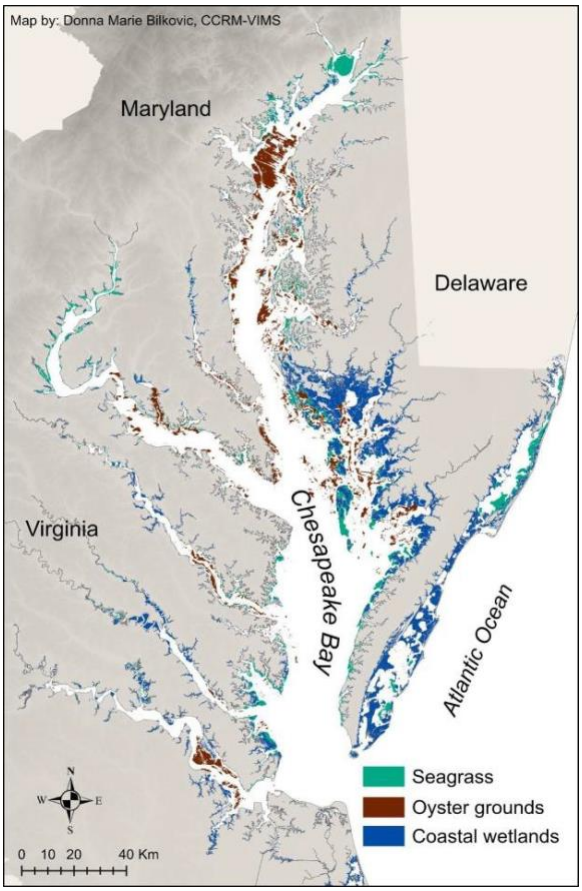

Figure 1. Segments adjacent to tidal waters in the Chesapeake Bay (shaded in the map). Map provided by CBPO Watershed Data Modeling Specialist, University of Maryland Center for Environmental Science (UMCES) (Bilkovic et al., 2019).

1.2 Barriers to Scaling NbS and Restoration in Coastal Practice

In the Chesapeake region and beyond, NbS approaches, including living shorelines, oyster reef construction, and marsh or seagrass restoration, are increasingly deployed as multifunctional

alternatives or complements to traditional grey infrastructure (Bilkovic & Mitchell, 2017; Hardaway Jr & Duhring, 2010). Unlike grey infrastructure, these approaches deliver a broad range of ecosystem services, from flood attenuation and water-quality improvement to carbon sequestration and recreation. Yet three compounding challenges continue to limit adoption:

- **Limited funding for, and inconsistency in, performance monitoring.** Monitoring beyond what is required for permit compliance is rarely funded, so post-implementation monitoring is often short-term or absent. Where monitoring does occur, approaches vary across projects and jurisdictions, and there is little consistent, actionable guidance on which measures best show whether a project is meeting its objectives. Together, these gaps limit cross-project learning, weaken adaptive management, and undermine confidence among planners, funders, and investors.
- **Unclear problem definition.** Unclear problem definition at the outset produces misaligned expectations, making it hard to demonstrate success even when a project performs as intended (Kurth et al., 2024; Olander et al., 2025).
- **Uncertain comparison with grey infrastructure.** Persistent uncertainty about how NbS compares to grey infrastructure on cost-benefit and return-on-investment grounds pushes decision-makers toward conventional engineered solutions, even where NbS could deliver equal or greater long-term value (Grabowski et al., 2012; Stroud et al., 2023). Resolving this uncertainty ultimately requires quantifying and valuing ecosystem services, which in turn depends on credible evidence that restored ecosystems are recovering the condition needed to deliver them.

Ecosystem condition, the quality of an ecosystem measured through its abiotic and biotic characteristics relative to a reference condition, is the critical link between restoration action and ecosystem service (ES) provision (United Nations, 2021). Recovery of ecological structure, composition, and processes supports the functions through which ecosystems generate services. Yet condition is rarely assessed with the consistency needed to support management decisions, and links between ecosystem state and ES provision remain difficult to quantify across local to regional scales (Grizzetti et al., 2019; Makowska et al., 2022).

Without a robust and validated set of indicators for tracking ecosystem condition and functional recovery, practitioners cannot consistently determine whether restoration and NbS are progressing toward intended outcomes or generate comparable evidence of performance across projects.

Changing environmental condition adds a further layer of difficulty. Many coastal ecosystems targeted for NbS, such as tidal marshes and seagrass beds, are themselves vulnerable to the same shifting conditions they are meant to help communities withstand, including sea-level rise, warming, and altered storm and sediment dynamics. This makes consistent, long-term monitoring even more essential: only by tracking conditions over time can practitioners detect early signs of ecosystem stress, adjust management strategies accordingly, and maximize service delivery while minimizing losses as environmental baselines continue to shift.

This guidebook does not resolve the funding constraint. Instead, it helps make the most of limited monitoring resources by linking indicators explicitly to project objectives, so that practitioners can focus on the measures most relevant to their intended outcomes. It also provides the ecological foundation needed for the valuation and cost-benefit comparisons identified as future work (Section 7).

1.3 About This Framework

This framework provides a unified set of performance indicators and scalable metrics that connect restoration and NbS objectives to measurable ecosystem condition, functional capacity, and intended outcomes. Developed through a scoping literature review and multiple rounds of expert engagement, it is designed to help practitioners select ecologically relevant measures, evaluate trajectories of recovery, and organize monitoring evidence so that it can support natural capital accounting and subsequent decision analyses. The indicators and metrics presented should not be considered all inclusive.

The framework is intended to complement, rather than replace, the monitoring and verification protocols established by the Chesapeake Bay Program (CBP) Best Management Practice (BMP) Expert Panels for crediting restoration practices under the Chesapeake Bay Total Maximum Daily Load (TMDL), such as those for shoreline management and oyster reef restoration (Expert Panel on Shoreline Management, 2019; Cornwell et al., 2023). A detailed comparison with these protocols is identified as future work (Section 7).

This synthesis focused more on *Habitat Quality & Ecosystem Integrity* and *Coastal Hazard Risk Reduction* NbS outcome dimensions. *Climate Mitigation* and *Socioeconomic Benefits*-related indicators and metrics were included when encountered and can be available for further inclusion in future work.

1.4 Intended Users and How to Use This Guidebook

This framework is intended for practitioners, managers, and decision-makers seeking structured guidance for linking coastal restoration monitoring with ecosystem condition assessment, NbS outcomes, and natural capital accounting. It does not prescribe a single monitoring protocol; instead, it provides a modular structure for selecting ecologically relevant indicators and metrics that can be adapted to project objectives, ecosystem type, scale, and monitoring capacity. Primary audiences include:

- Local and state government coastal managers responsible for long-term shoreline stewardship
- Planners evaluating NbS proposals and outcomes
- Restoration practitioners seeking consistent, defensible approaches to performance documentation
- Community organizations and NGOs leading or supporting NbS projects
- Coastal property owners and stewards engaged in voluntary restoration
- Funding agencies and investors requiring credible, longitudinal evidence of returns on NbS investments

No user is expected to apply every component. The modular structure allows different audiences to use the elements most relevant to their decisions, for example, a coastal manager selecting indicators for a site-level assessment, an analyst organizing monitoring evidence for SEEA EA condition accounts, or a regional agency developing a portfolio-scale monitoring strategy.

2. Framework Foundations

2.1 Ecosystem Typology as Foundation

This framework draws on the IUCN Global Ecosystem Typology (GET) as its classificatory foundation (Kurth et al., 2024; Olander et al., 2025). The GET is a hierarchical system that organizes ecosystems according to their functional characteristics, biotic composition, and the ecological processes that sustain them. Using the GET was a deliberate methodological choice: it provides an internationally recognized vocabulary for defining ecosystem identity (that is, classifying a site as a particular ecosystem type, such as a seagrass meadow or a saltmarsh) and, critically, a consistent ecological basis for identifying and interpreting appropriate reference conditions against which restoration outcomes and ecosystem condition can be assessed and compared across sites, scales, and governance contexts.

For the Chesapeake Bay region, a subset of GET functional groups was selected based on ecological relevance and restoration and management priority: seagrass meadows, shellfish beds and reefs, and coastal saltmarshes. Future work will expand to the remaining functional groups relevant to the region, including sandy shorelines and coastal shrublands and grasslands, broadening the framework's coverage and utility for managers working across the full range of coastal ecosystem types (Keith et al., 2020; Olander et al., 2025).

Anchoring performance indicators and metrics to GET functional groups, rather than to administratively defined habitat categories or NbS types, grounds assessment in ecologically meaningful ecosystem characteristics. Because these groups are defined by ecological criteria rather than political boundaries, they provide a consistent basis for comparing restoration performance across the Chesapeake Bay's jurisdictional mosaic while retaining the specificity needed to identify appropriate condition characteristics and reference conditions.

2.2 Distinguishing Nature-based Solutions from Ecological Restoration

Nature-based solutions (NbS) and ecological restoration are closely related but distinct concepts, and conflating them can obscure important differences in their objectives, implementation, and evaluation (Waylen et al., 2024). Ecological restoration, as defined by the Society for Ecological Restoration and the IUCN Commission on Ecosystem Management, focuses primarily on assisting the recovery of degraded ecosystems by re-establishing ecological processes, functions, and biodiversity (Gann & Lamb, 2006).

NbS, by contrast, are defined by the IUCN as actions that protect, sustainably manage, or restore natural and modified ecosystems to address societal challenges while simultaneously supporting human well-being and biodiversity (IUCN, 2026). The concept encompasses a broader range of approaches, including ecological restoration, green infrastructure, Engineering with Nature, and catchment-based strategies such as natural flood management (Jones et al., 2022). The key distinction therefore lies in the primary framing of the intervention: restoration centers on ecosystem recovery, whereas NbS are explicitly designed to address one or more societal challenges through the protection, management, or restoration of ecosystems. Restoration can consequently function as an NbS when ecological recovery is deliberately undertaken to address a defined societal challenge (Sowińska-Świerkosz & García, 2022).

2.3 From Biophysical Structure to Ecosystem Service Outcomes

Many coastal restoration projects in the Chesapeake Bay pursue ecological recovery alongside societal objectives such as reducing coastal hazards, improving water quality, or enhancing climate resilience. Within this framework, restoration is therefore treated as an ecological mechanism through which NbS outcomes can be achieved, and performance is evaluated by asking whether recovery is sufficient to support the functions, services, and benefits associated with those objectives.

The framework represents this relationship as a causal pathway from ecosystem structure and condition to societal benefit. Restoration modifies or recovers biophysical and biological attributes of ecosystem condition, for example, vegetation structure and root/rhizome development in saltmarshes, shoot density and belowground biomass in seagrass meadows, or vertical relief and structural complexity in oyster reefs. These attributes influence ecological functions, including wave attenuation, sediment trapping and accretion, nutrient cycling, primary production, and habitat support.

Ecological functions support ecosystem service flows when they contribute to benefits valued by people. Wave attenuation and sediment stabilization, for example, contribute to coastal protection, while nutrient cycling and filtration contribute to water-quality regulation. Those services can in turn generate societal benefits such as avoided flood damages, improved recreational opportunities, enhanced fisheries, and cultural or aesthetic value.

In ecosystem accounting, an **ecosystem service flow** is the quantity of a service that an ecosystem supplies and that people or economic units use during an accounting period, for example, the reduction in wave energy reaching a shoreline or the tonnes of sediment retained by a marsh in a given year (United Nations, 2021). Service flows are distinct from the ecosystem asset itself, which is a stock described by its extent and condition.

The pathway can therefore be conceptualized as ecosystem structure and condition → ecological function → ecosystem service → societal benefit. Because sustained service delivery depends on functional capacity, and functional capacity depends on ecosystem condition, restoration monitoring must capture more than implementation or end-point benefits. It must provide evidence that the ecological attributes and processes needed to sustain intended outcomes are recovering over time.

This pathway provides the conceptual basis for the framework's four outcome dimensions: (1) coastal hazard risk reduction, (2) climate mitigation, (3) habitat quality and ecosystem integrity, and (4) socioeconomic benefits (Table 1). Together, they span ecosystem conditions, service delivery, and associated human benefits. Habitat quality and ecosystem integrity represents the state of the ecosystem asset itself, whereas the other dimensions capture outcomes associated with ecosystem services and their benefits. This organization allows managers to connect desired NbS outcomes with the ecological evidence needed to evaluate whether they can be sustained.

Table 1. The framework's four outcome dimensions, their relevance to SEEA EA accounting categories, and representative coastal benefits. Habitat quality and ecosystem integrity reflects ecosystem condition (the state of the asset itself); the other three dimensions correspond to ecosystem service flows delivered to people.

Outcome dimension	Definition	SEEA EA relevance	Example coastal benefits
Coastal Hazard Risk Reduction	The capacity of an ecosystem to buffer coastal communities and infrastructure from physical hazards such as flooding, erosion, and storm surge.	Ecosystem service flow	Wave attenuation, shoreline stabilization, storm surge buffering
Climate Mitigation	The capacity of an ecosystem to remove and store atmospheric carbon, reducing net greenhouse gas emissions.	Ecosystem service flow	Carbon sequestration and storage in marsh soils and vegetation
Habitat Quality & Ecosystem Integrity	The structural and functional condition of the ecosystem itself, relative to a reference or desired state.	Ecosystem condition (asset state, not a service flow)	Vegetation cover, species diversity, structural complexity, functional recovery
Socioeconomic Benefits	The direct and indirect value ecosystems provide to people and local economies.	Ecosystem service flow	Recreational access, commercial fisheries productivity, property value protection, cultural/community value

The framework operationalizes this causal pathway by using GET functional groups to identify the ecological functions most relevant to restoration and NbS performance. The central monitoring question is:

Is restoration recovering the ecosystem condition and functional capacity needed to sustain the intended services?

Answering this question requires identifying which functions underpin each targeted service and which measurable condition characteristics provide evidence that those functions can be sustained. This function-to-service linkage forms the analytical core of the framework (Figure 2). Performance is therefore evaluated against ecological recovery rather than the physical work completed alone. For example, living shoreline restoration can be linked to sediment stabilization, accretion, and wave attenuation that contribute to coastal protection, while submerged aquatic vegetation restoration can be linked to primary productivity, nutrient uptake, sediment stabilization, and habitat structure associated with water-quality regulation and habitat-related outcomes.

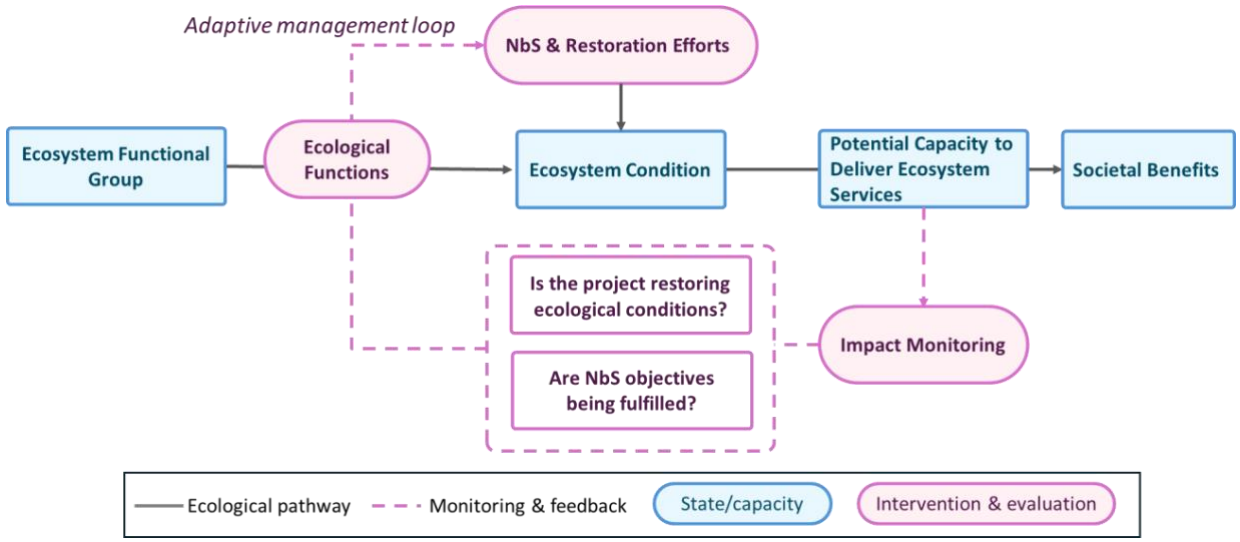

Figure 2. Conceptual framework linking ecosystem function and condition to service delivery. Restoration efforts improve ecosystem condition, increasing the capacity to deliver ecosystem services; impact monitoring evaluates ecosystem condition trends and whether ecosystem services are being met and fulfilling the NbS objectives. This feeds back into adaptive management under changing climatic and environmental conditions.

Primary and secondary linkages. For each ecosystem, Sections 3–5 summarize which ecosystem services contribute to each outcome dimension. A *primary linkage* is a major pathway through which the ecosystem contributes to an outcome dimension, consistently supported by empirical evidence and broad expert agreement. A *secondary linkage* is a complementary, indirect, or more context-dependent contribution that may vary spatially or temporally, depend on site conditions or restoration design, or be less consistently supported across the evidence reviewed. Linkages were classified by synthesizing the scientific literature with expert input from the charrettes.

2.4 Aligning Monitoring with Natural Capital Accounting

Natural capital accounting (NCA) offers a structured way to organize this evidence by tracking changes in ecosystem extent and condition and linking them to ecosystem service delivery and contributions to human well-being over time (United Nations, 2021; Obst et al., 2016; Mace et al., 2015). NCA treats ecosystems as assets, for instance, areas of marsh, reef, or seagrass that are relatively homogeneous in ecosystem type and condition, whose extent and condition influence their capacity to generate ecosystem services over time. Restoration monitoring can therefore contribute standardized information on ecosystem extent, condition, and service delivery that can subsequently support economic valuation and other decision-relevant analyses (Obst et al., 2016; Wielgus et al., 2023).

The System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA EA) is the internationally adopted statistical framework that operationalizes ecosystem accounting (United Nations, 2021). It organizes information into linked accounts that can be tracked consistently over time and connected with economic accounts. Three types of account are central: **extent** accounts record the area of each ecosystem type; **condition** accounts record the ecological characteristics of each ecosystem relative to reference conditions; and **ecosystem service** accounts record the services ecosystems supply

and who uses them, in physical and, where appropriate, monetary terms. Monetary asset accounts can then estimate the value of an ecosystem asset from its expected future stream of services.

The framework is designed to support SEEA EA ecosystem condition accounting by generating standardized evidence on the state and trajectory of restored ecosystem assets. Condition accounts organize ecosystem characteristics relative to reference conditions, providing a systematic basis for tracking ecological change over time. For NbS, this longitudinal perspective is particularly important because performance depends on maintaining ecological capacity well beyond initial implementation.

Indicators are structured to facilitate integration with SEEA EA condition accounting. They can be mapped to relevant ecosystem condition characteristics, referenced against scientifically grounded baselines or appropriate reference levels, and tracked longitudinally. Because their selection follows the function-to-service logic described above, the indicators emphasize condition characteristics that are relevant to targeted outcomes rather than serving only as generic descriptors of ecological state. With appropriate spatial attribution, aggregation, and harmonization, monitoring data can contribute to condition accounts and strengthen their connection with ecosystem service accounts.

This alignment creates a progression from restoration monitoring to natural capital accounting and, where appropriate, valuation. Condition measures document biophysical change; ecosystem service accounts can then connect those changes to service supply and use; and monetary valuation can express selected service flows in economic terms (Figure 3). For the Chesapeake Bay region, this progression can provide a more consistent evidence base for cost-benefit analysis, investment comparisons, planning, and long-term funding decisions without requiring every ecological measure to be monetized.

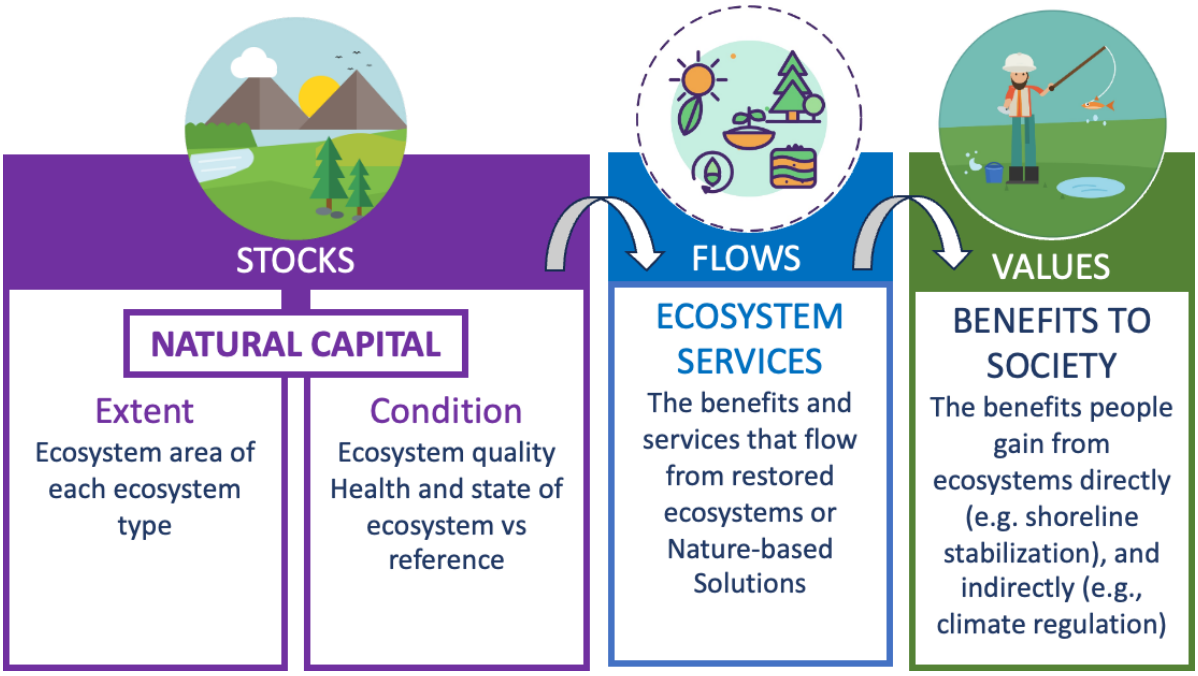

Figure 3. Diagram showing the relationship between natural capital (stocks), ecosystem services (flows) and valuation (benefits).

For the Chesapeake Bay watershed, aligning coastal monitoring with SEEA EA can provide a common framework for organizing evidence on whether restoration investments are maintaining or improving

the region's natural capital base. Connecting changes in ecosystem extent and condition with service delivery can also strengthen the evidence available for evaluating the long-term contribution of restoration and NbS to coastal resilience (Obst et al., 2016; Wielgus et al., 2023). This alignment is especially relevant in the Chesapeake Bay, where restoration occurs across multiple jurisdictions, ecosystem types, and monitoring programs. A common accounting structure can make ecological changes more comparable and visible to managers, funders, and policymakers by connecting measures such as water clarity, marsh extent, or shoreline stability with changes in ecosystem condition and, where evidence permits, associated services such as flood-risk reduction, carbon storage, fisheries support, and recreation.

2.5 Performance Indicators and Metrics

Evaluating NbS effectiveness requires distinguishing the outcome or condition being assessed from the metric used to measure it.

- **Performance indicators** identify what aspect of performance is being assessed, for example, shoreline stabilization or water-quality improvement.
- **Metrics** specify how that performance is measured and compared across sites or over time. A single indicator may be represented by multiple metrics: shoreline stabilization, for example, may be assessed using erosion rate (m yr^{-1}), shoreline-position change relative to a fixed baseline, or vegetation cover (%), depending on the monitoring objective and ecosystem context.

Maintaining this distinction allows practitioners to begin with the management or performance question and then select feasible metrics that provide evidence relevant to that question, rather than collecting measurements without a clear analytical purpose.

The indicators and metrics identified for the three ecosystem typologies considered in this study (seagrass meadows, oyster beds and reefs, and coastal saltmarshes and reedbeds) were derived through an extensive scoping literature review, with the full set of references consulted provided in Appendix A. This literature-based foundation was subsequently validated and refined through a series of stakeholder engagement activities, including two design charrettes, a workshop organized at Environment Virginia, and a set of semi-structured interviews. Outputs from the charrettes are summarized in Appendix B. This combined approach ensured that the selected indicators and metrics reflect both the current state of scientific knowledge and the practical insights and priorities of regional stakeholders and practitioners.

3. Seagrass Meadows and Submerged Aquatic Vegetation

3.1 Definition and Regional Context

Within the Chesapeake Bay, submerged aquatic vegetation (SAV) is the term used collectively for submerged vascular plant communities occurring across the Bay's salinity gradient, from marine and polyhaline waters to tidal freshwater systems (Batiuk et al., 2000; Kemp et al., 2004) (Figure 4). This broader SAV category includes seagrass meadows, which represent the marine and higher-salinity portion of this gradient and correspond most closely to the seagrass ecosystem types recognized within the IUCN Global Ecosystem Typology (GET) (Keith et al., 2020). Marine and higher-salinity communities are dominated by eelgrass (*Zostera marina*) and widgeon grass (*Ruppia maritima*), whereas lower-salinity and tidal freshwater habitats support diverse submerged plant communities, including wild celery (*Vallisneria americana*). These plant communities are central to regional restoration and watershed management goals (Kemp et al., 2004; Orth et al., 2017a).

Figure 4. Submerged aquatic vegetation fish habitat in the Chesapeake Bay. Photo credit: Chesapeake Bay Program.

3.2 Ecosystem Services

SAV meadows are among the most productive ecosystems in estuarine environments. They stabilize sediments, improve water quality by trapping suspended particles and cycling nutrients, provide critical habitat and nursery grounds for fish, shellfish, and waterfowl, and reduce wave energy, thereby contributing to shoreline stabilization (do Amaral Camara Lima et al., 2023). Because their distribution and condition respond sensitively to changes in water quality, light availability, temperature, and physical disturbance, SAV also serves as a key indicator of estuarine ecosystem health and a priority target for restoration throughout the Chesapeake Bay region (Nordlund et al., 2018). Table 2 summarizes how these services contribute to the framework's outcome dimensions.

Table 2. Ecosystem services provided by seagrass meadows and SAV across NbS outcome dimensions (● primary linkage; ○ secondary linkage; see Section 2.3 for definitions).

Ecosystem service	Coastal hazard risk reduction	Climate mitigation	Habitat quality & ecosystem integrity	Socioeconomic benefits
Water-quality enhancement			●	○
Habitat support			●	○
Fisheries support			●	○
Climate regulation		●		
Shoreline protection	○			○

Habitat support, fisheries production, and water-quality regulation were identified as primary linkages because they represent well-established pathways through which SAV condition and ecological functioning contribute to ecosystem integrity and associated benefits. For example, the structural complexity of SAV provides habitat and nursery areas for aquatic organisms, while nutrient uptake, sediment stabilization, and related processes contribute to water-quality regulation. These ecological pathways can subsequently generate socioeconomic benefits, including recreational and commercial fisheries value, making their contribution to the socioeconomic benefits outcome dimension primarily indirect. Shoreline protection was similarly classified as a secondary linkage to coastal hazard risk reduction. Although SAV can attenuate wave energy and stabilize sediments, the magnitude of these effects is context dependent and generally less pronounced than the protective functions associated with more structurally complex coastal habitats and interventions, such as tidal marshes, oyster reefs, and living shorelines.

3.3 Characteristics of an SAV Meadow in Good Ecological Condition

An SAV meadow in good ecological condition is characterized by clear water, abundant plant growth, and a stable underwater environment that supports diverse aquatic life. Good water quality allows enough sunlight to reach the plants, enabling them to grow into dense, continuous meadows with high shoot density, healthy biomass, and well-developed canopies (Batiuk et al., 2000; Kemp et al., 2004; Orth et al., 2017a). These conditions also promote flowering and natural reproduction, helping maintain resilient and self-sustaining SAV populations (Marion & Orth, 2010; van Katwijk et al., 2016).

Good ecological conditions are also reinforced by positive feedback between SAV and its surrounding environment. Dense vegetation reduces water movement and resuspension, promotes sediment stabilization, and contributes to nutrient cycling, helping maintain the water clarity required for continued plant growth (Lefcheck et al., 2018; Gurbisz & Kemp, 2014). Low epiphytic algal loads further support light availability at the leaf surface (Kemp et al., 2004; Jasinski et al., 2021). At the meadow scale, spatially extensive and well-connected SAV beds provide structurally complex habitat capable of supporting diverse fish, blue crab, and other aquatic communities, providing additional evidence of ecosystem integrity and functional condition (Lefcheck et al., 2017; Schaffler et al., 2013; Unsworth et al., 2019; Orth et al., 2020).

3.4 Restoration and Management Approaches

Restoration and management approaches for SAV span a continuum from protecting existing meadows and improving the environmental conditions that support their persistence to actively re-establishing vegetation in areas where SAV has been lost (Orth et al., 2017b; Jasinski et al., 2021). When these interventions are undertaken to address societal challenges alongside ecological recovery, such as improving water quality, supporting fisheries, enhancing carbon sequestration, or contributing to coastal resilience, they can function as NbS (Forrester et al., 2024). In the Chesapeake Bay, long-term monitoring indicates that sustained SAV recovery has been driven primarily by watershed-scale improvements in water quality, particularly reductions in nutrient and sediment inputs associated with implementation of the Total Maximum Daily Load (TMDL) framework (Orth et al., 2010; Orth et al., 2017a; Lefcheck et al., 2018). These improvements restore the light and habitat conditions necessary for natural recolonization and are also critical to the success of active restoration (Batiuk et al., 2000; Kemp et al., 2004).

Where environmental conditions are suitable but natural recovery is limited, active restoration can accelerate SAV establishment. Two primary techniques have been applied in the Chesapeake Bay:

Seed-based restoration. This approach involves collecting seeds from healthy donor meadows and distributing them across suitable restoration sites where SAV has been lost (Marion & Orth, 2010; Orth et al., 2020; Jasinski et al., 2021). Seeds are collected from flowering plants, stored until planting, and then broadcast across restoration areas to promote establishment. Although specialized harvesting equipment can improve collection efficiency, seed collection in much of the Chesapeake Bay is conducted manually because many donor and restoration sites are shallow and difficult to access with mechanical equipment (Marion & Orth, 2010).

Shoot transplantation. This method involves planting vegetative shoots or plugs directly into the sediment to establish new SAV beds (Orth et al., 2020). Transplants may be placed in clusters to enhance establishment and stability under suitable site conditions, particularly where waves and currents influence plant survival (van Katwijk et al., 2016).

Regardless of the technique used, active restoration cannot substitute for suitable environmental conditions. Seed broadcasting and transplantation are most likely to result in persistent SAV meadows where water clarity, light availability, sediment conditions, and other environmental characteristics are sufficient to support plant establishment, growth, and natural expansion (Batiuk et al., 2000; Jasinski et al., 2021). Active restoration should therefore be viewed as complementary to, rather than a replacement for, the broader watershed management actions required to maintain suitable SAV habitat.

3.5 Performance Indicators and Metrics

Based on a review of the scientific literature and practitioner knowledge, we identified a set of ecological condition characteristics, functional pathways, and ecosystem services through which SAV contributes to NbS outcomes in the Chesapeake Bay. These were organized across three of the framework's broader outcome dimensions: Habitat Quality & Ecosystem Integrity, Climate Mitigation, and Coastal Hazard Risk Reduction. Within Habitat Quality & Ecosystem Integrity, the framework distinguishes the environmental conditions necessary for SAV establishment and persistence from

measures of meadow condition and structural integrity and the habitat and fisheries functions supported by healthy SAV. Climate mitigation and coastal hazard risk reduction are represented through carbon storage and wave attenuation and sediment stabilization pathways, respectively. For each pathway, performance indicators and associated metrics provide evidence of ecosystem condition, functional capacity, and, where appropriate, service delivery. This structure enables practitioners to evaluate whether restored SAV meadows are developing and maintaining the ecological capacity needed to support their intended NbS outcomes. The indicators are listed in Table 3.

Table 3. Performance indicators and metrics for SAV restoration monitoring, organized by NbS outcome dimension and function–service pathway.

Function–service pathway	Performance indicator	Metric (unit)
Habitat Quality & Ecosystem Integrity		
Enabling environmental conditions	Light availability	Light attenuation coefficient (Kd, m^{-1}); % surface irradiance at depth; photosynthetically active radiation (PAR, µmol m^{-2} s^{-1})
	Water clarity	Total suspended solids (TSS, mg L^{-1}); Secchi depth (m)
	Nutrient conditions	Total nitrogen (TN, mg L^{-1}); total phosphorus (TP, mg L^{-1})
	Phytoplankton abundance	Chlorophyll a (µg L^{-1})
	Dissolved oxygen	Dissolved oxygen (mg L^{-1})
Meadow condition and structural integrity*	Meadow extent	Area (ha); total planform field area (ha)
	Vegetation cover	SAV cover per plot (%)
	Shoot density	Number of shoots (shoots m^{-2})
	Canopy structure	Mean shoot height (cm)
	Biomass	Aboveground dry weight (g m^{-2}); belowground dry weight (g m^{-2})
	Species composition	Presence and relative abundance of *Z. marina* and *R. maritima*
	Reproductive capacity	Flowering shoot density (shoots m^{-2})
	Spatial integrity / patch dynamics	Patch size distribution (ha); fragmentation index
	Epiphyte load	Epiphyte load (mg dry weight cm^{-2} leaf area)
Habitat and fisheries support	Species community diversity	Shannon–Wiener diversity index (H')
	Juvenile blue crab abundance	Juvenile blue crab density (individuals m^{-2})
	Juvenile fish and crustacean abundance	Juvenile density of selected species (individuals m^{-2})
	Nekton biomass	Total nekton biomass per unit area (g DW m^{-2})
Climate Mitigation		
Carbon storage	Carbon stocks	Soil organic carbon stock to 1-m depth (Mg C ha^{-1}); aboveground and belowground biomass carbon (g C m^{-2})
Coastal Hazard Risk Reduction		
Wave attenuation and sediment stabilization	Wave attenuation	Incident-to-transmitted wave-energy reduction (%)
	Sediment accretion	Vertical sediment accumulation (mm yr^{-1})

Function–service pathway	Performance indicator	Metric (unit)
	Shoreline response	Shoreline change rate (m yr^{-1})
Socioeconomic Benefits		
Economic activity: restoration/intervention	Direct restoration employment	Number of restoration jobs supported by project
Economic activity: recreation and tourism	Recreational expenditure change	Change in recreational activity and recreational fishing expenditures associated with project-site visitation

*Charrette participants recommended that routine monitoring of meadow condition and structural integrity occur once a year, timed to coincide with peak biomass for the species present. In the Chesapeake Bay this means late spring to early summer for eelgrass (*Zostera marina*) and late July through early August for widgeon grass (*Ruppia maritima*), reflecting their distinct phenological cycles. Surveys outside these windows risk underestimating cover and biomass and can obscure real trends in bed condition.

4. Shellfish Beds and Oyster Reefs

4.1 Definition and Regional Context

Within the IUCN Global Ecosystem Typology (GET), shellfish beds and reefs are biogenic ecosystems formed through the accumulation and growth of shell-producing organisms. In the Chesapeake Bay, restoration and Nature-based Solutions (NbS) efforts involving shellfish are focused predominantly on the eastern oyster (*Crassostrea virginica*).

Accordingly, this framework uses *oyster reefs* when referring specifically to eastern oyster-dominated systems in the Chesapeake Bay, while *shellfish beds and reefs* refers to the broader GET ecosystem classification. Eastern oysters form persistent three-dimensional reef structures that provide habitat for diverse fish and invertebrate communities and are an important component of Chesapeake Bay restoration and ecosystem management.

Figure 5. Restoration project using oyster castles along Knitting Mill Creek in Norfolk, VA. Photo credit: Laura Costadone.

4.2 Ecosystem Services

Oyster reefs support multiple ecological functions and ecosystem services relevant to NbS outcomes in the Chesapeake Bay, including water-quality regulation, nutrient cycling, habitat and fisheries support,

shoreline protection, and potential climate-regulation benefits (Table 4). The relative importance of these contributions varies with reef condition, location, and restoration design. For example, shoreline protection is particularly relevant to intertidal and nearshore reefs, whereas subtidal reefs are more commonly associated with water-quality regulation, habitat support, and fisheries production. The magnitude and persistence of these services ultimately depend on the development and maintenance of healthy, structurally complex reefs under suitable environmental and management conditions.

Table 4. Ecosystem services provided by shellfish beds and oyster reefs across NbS outcome dimensions (● primary linkage; ○ secondary linkage; see Section 2.3).

Ecosystem service	Coastal hazard risk reduction	Climate mitigation	Habitat quality & ecosystem integrity	Socioeconomic benefits
Water-quality enhancement			●	●
Nutrient cycling and removal		○	●	○
Habitat support / ecosystem health			●	○
Fisheries support			●	●
Carbon storage and sequestration		○		
Shoreline protection and erosion reduction (mostly intertidal restoration)	●			○

For oyster reefs, water-quality regulation, nutrient cycling, habitat support, and fisheries support were identified as primary linkages to Habitat Quality & Ecosystem Integrity. Water-quality regulation and fisheries support also contribute directly to Socioeconomic Benefits, particularly through commercial and recreational fisheries and recreation, while nutrient cycling and habitat support contribute more indirectly by maintaining the ecological conditions that underpin these benefits. Shoreline protection was identified as the primary linkage to Coastal Hazard Risk Reduction, particularly for intertidal and nearshore reefs designed to attenuate wave energy and reduce erosion. Potential contributions to Climate Mitigation, including carbon storage and climate-related effects of nutrient cycling, were classified as secondary because these pathways are more context dependent and generally less prominent than in vegetated coastal ecosystems such as tidal marshes and seagrass meadows.

4.3 Characteristics of an Oyster Reef in Good Ecological Condition

An oyster reef in good ecological condition is characterized by a persistent three-dimensional structure and a self-sustaining oyster population capable of maintaining that structure over time. Healthy reefs support abundant live oysters across multiple size and age classes, continued recruitment, and sufficient shell production and accumulation to offset losses from mortality, shell degradation, and erosion (Schulte et al., 2009; Allen et al., 2011; Waldbusser et al., 2011; Baggett et al., 2014). Well-developed vertical relief and structural complexity provide settlement surfaces for new oysters and habitat for diverse fish, crabs, and other aquatic organisms (Coen & Luckenbach, 2000).

Good ecological condition also depends on environmental factors that support oyster survival, growth, recruitment, and reef persistence. These include suitable salinity, adequate dissolved oxygen, manageable sedimentation, appropriate substrate, and tolerable levels of disease and other biological stressors (Carnegie & Burreson, 2011; Baggett et al., 2014). Together, oyster abundance and population structure, recruitment, reef morphology, and associated biological communities provide evidence of whether restoration is progressing toward a persistent and functionally capable reef. Maintaining this condition allows oyster reefs to sustain the filtration, nutrient cycling, habitat support and, where appropriately located, wave attenuation and sediment stabilization functions that underpin their intended NbS outcomes.

4.4 Restoration and Management Approaches

Restoration and management approaches for oyster reefs span a continuum from protecting and managing existing reefs to rebuilding degraded reef structure and actively establishing oyster populations where natural recovery is limited. The appropriate approach depends on environmental conditions, restoration objectives, and reef position within the estuarine landscape. In the Chesapeake Bay, two broad restoration settings are particularly relevant: subtidal reef restoration and intertidal or nearshore oyster restoration, including oyster-based living shoreline applications.

Subtidal reef restoration

This approach establishes or rebuilds oyster reefs below the intertidal zone, typically by placing oyster shells or alternative hard substrates on the bottom to provide settlement surfaces for oyster larvae. Where natural recruitment is insufficient, reefs may also be seeded with hatchery-produced juvenile oysters. This work happens mainly in protected areas where harvesting oysters is off-limits, so the reefs have time to grow tall and complex and eventually reproduce on their own (Allen et al., 2011).

For large projects, crews use boats fitted with conveyor systems to spread shells evenly over large areas. Some projects also use built structures like reef balls or "oyster castles", concrete or shell-based blocks stacked to form a 3D reef. Raising the reef up off the bottom like this matters because water near the bottom can run low on oxygen, which kills young oysters. Structures that lift oysters up into better-oxygenated water help more of them survive, and as living oysters build up, they help attract even more oyster larvae to settle nearby, so the reef keeps growing (Allen et al., 2011; Bruce et al., 2021).

Intertidal oyster restoration and living shorelines

This approach places substrate, like rocks and shell, or engineered reef structures, such as oyster castles, bagged shell, and reef balls, along eroding shorelines, usually paired with plantings of native marsh grass. The structures give wild oyster larvae a stable surface to settle on right away, while also stabilizing the shoreline and reducing wave energy before it reaches the marsh (CCRM, 2024). Removing oysters lowers the reef crest and weakens its ability to break waves, so keeping the structure intact is essential to the design. Here, coastal protection is the main goal and oyster settlement is a valuable byproduct, not the primary purpose (TNC, 2021).

4.5 Performance Indicators and Metrics

Based on a review of the scientific literature and practitioner knowledge, we identified a set of ecological condition characteristics, functional pathways, and ecosystem services through which oyster reefs contribute to NbS outcomes in the Chesapeake Bay. These were organized across the framework's broader outcome dimensions of Habitat Quality & Ecosystem Integrity, Coastal Hazard Risk Reduction, Climate Mitigation, and Socioeconomic Benefits. Within Habitat Quality & Ecosystem Integrity, the framework distinguishes environmental conditions necessary for oyster survival and reef persistence from measures of oyster population condition, reef structural integrity, and the habitat and fisheries functions supported by healthy reefs. Coastal hazard risk reduction is represented primarily through wave attenuation, sediment stabilization, and shoreline protection pathways, particularly for intertidal and nearshore reefs, while potential climate-mitigation contributions are treated as secondary and context dependent. For each pathway, performance indicators and associated metrics provide evidence of ecosystem condition, functional capacity, and, where appropriate, service delivery.

Environmental parameters such as temperature, salinity, and dissolved oxygen are treated primarily as conditions supporting reef recovery, rather than direct measures of restoration performance. In contrast, measures such as live oyster density, recruitment, population structure, reef relief, and structural persistence provide more direct evidence of whether the restored reef is developing toward good ecological condition (Baggett et al., 2014).

The relevance of environmental variables varies with restoration settings. Dissolved oxygen, for example, can be particularly important for interpreting the performance of deeper subtidal reefs exposed to seasonal stratification and hypoxia, whereas shallow intertidal and nearshore sites generally experience greater tidal mixing (Allen et al., 2011; CCRM, 2024). Environmental variables should therefore be monitored where relevant as contextual or enabling conditions for interpreting reef performance. This structure enables practitioners to distinguish whether poor performance reflects unsuitable environmental conditions or inadequate biological and structural recovery and to evaluate whether restored oyster reefs are developing the ecological capacity needed to sustain their intended NbS outcomes.

Table 5. Performance indicators and metrics for oyster reef restoration monitoring, organized by NbS outcome dimension and function–service pathway. S = primarily applicable to subtidal restoration; I = primarily applicable to intertidal or nearshore restoration and living shorelines; no designation indicates applicability to both.

Function–service pathway	Performance indicator	Metric (unit)
Habitat Quality & Ecosystem Integrity		
Environmental conditions supporting oyster reef recovery	Dissolved oxygen (S)	Dissolved oxygen (mg L^{-1}); oxygen saturation (%)
Oyster population condition and reef structural integrity	Oyster population abundance	Live oyster density (individuals m^{-2})
	Oyster population structure	Oyster size-frequency distribution
	Oyster biomass	Estimated biomass (kg DW m^{-2})
	Reef extent	Reef area (m^2)
	Reef structural complexity	Reef height or vertical relief (m); structural volume or mass (m^3 or tons of structural base)

Function–service pathway	Performance indicator	Metric (unit)
	Reef structural persistence	Shell budget (m^3 yr^{-1})
	Target species coverage	Target species field cover (%)
Associated benthic community and habitat support	Benthic community abundance	Macrofaunal or macroinvertebrate density (organisms m^{-2})
	Benthic community diversity	Taxonomic richness; Shannon–Wiener diversity index (H′)
	Associated organism density	Structural crowding density (individuals m^{-2})
Water-quality regulation	Water clarity	Change in vertical light attenuation coefficient (Kd, m^{-1}); change in % surface irradiance penetration
	Suspended sediment concentration	Total suspended solids (TSS, mg L^{-1}); Secchi depth (m)
	Phytoplankton abundance	Change in chlorophyll a (µg L^{-1} d^{-1})
	Nutrient concentrations	Total nitrogen (TN, mg L^{-1}); total phosphorus (TP, mg L^{-1})
Nutrient cycling	Denitrification	Sediment denitrification rate (mg N m^{-2} d^{-1})
	Sediment nutrient flux	Dissolved inorganic nitrogen (DIN) flux (mg N m^{-2} d^{-1})
Habitat and fisheries support	Fish community diversity	Shannon–Wiener diversity index (H′); presence or absence of target fish species
	Crab abundance / nursery support	Resident crab density (individuals m^{-2})
	Juvenile fish and crustacean abundance	Juvenile density of target species (individuals m^{-2})
Coastal Hazard Risk Reduction		
Wave attenuation and sediment stabilization	Wave attenuation (I)	Incident-to-transmitted wave-energy reduction (%)
	Sediment accretion (I)	Vertical sediment accretion rate (mm yr^{-1})
Socioeconomic Benefits		
Economic activity: restoration/intervention	Direct restoration employment	Number of restoration jobs supported by project (# FTEs yr^{-1})
Economic activity: recreation and tourism	Change in economic activity from recreational and commercial fishing (S)	Change in economic activity from recreational fishing and project-associated commercial harvest ($ yr^{-1}, before vs. after restoration)
Property protection	Property adjacent to shoreline with reduced erosion (I)	Linear feet or miles of shoreline, or acreage of upland protected, paired with erosion rate before vs. after (ft yr^{-1})
Property value	Change in property value across affected properties (I)	$ change in assessed or market value, or % change relative to comparable non-adjacent properties

5. Coastal Saltmarshes and Reedbeds

5.1 Definition and Regional Context

Within the IUCN Global Ecosystem Typology (GET), coastal saltmarshes and reedbeds are intertidal wetland ecosystems occurring along sheltered shorelines, estuaries, and tidal tributaries. In the Chesapeake Bay, saltmarsh vegetation varies along gradients of salinity, elevation, and tidal inundation. Saltmarshes are commonly dominated by salt-tolerant species such as smooth cordgrass (*Spartina alterniflora*) and saltmeadow cordgrass (*Spartina patens*), while reedbeds may be dominated by common reed (*Phragmites australis*) in brackish and tidal freshwater environments (Figure 6). Although *P. australis* is included within the broader reedbed classification, invasive populations are widespread in the Chesapeake Bay region and can pose a significant threat to native tidal-wetland communities by displacing native vegetation and altering habitat structure and ecosystem processes (Hazelton et al., 2014; Kettenring et al., 2012). Its presence should therefore be distinguished from the native vegetation characteristics associated with good ecological condition and may represent a target for management or restoration.

Figure 6. Lynnhaven River, Virginia Beach, VA. Photo credit: NOAA Chesapeake Bay Office.

5.2 Ecosystem Services

Coastal saltmarshes and reedbeds support multiple ecological functions and ecosystem services relevant to NbS outcomes in the Chesapeake Bay (Table 6). Vegetation and marsh soils trap and stabilize sediments, attenuate wave energy, cycle and retain nutrients, store carbon, and provide habitat for fish, birds, invertebrates, and other wildlife. Through these functions, tidal wetlands contribute to water-quality regulation, habitat and fisheries support, climate mitigation, and coastal hazard risk reduction.

The magnitude and persistence of these contributions depend on marsh condition and the capacity of the wetland to maintain its vegetation, elevation, and hydrologic connectivity as environmental conditions change.

Table 6. Ecosystem services provided by coastal saltmarshes and reedbeds across NbS outcome dimensions (● primary linkage; ○ secondary linkage; see Section 2.3).

Ecosystem service	Coastal hazard risk reduction	Climate mitigation	Habitat quality & ecosystem integrity	Socioeconomic benefits
Water-quality enhancement			●	●
Nutrient cycling and removal		○	●	○
Habitat support / ecosystem health			●	○
Fisheries support			●	●
Carbon storage and sequestration		●		
Shoreline protection and erosion reduction	●			○

For coastal saltmarshes and reedbeds, water quality enhancement, nutrient cycling, habitat and fisheries support were identified as the primary ecosystem services supporting Habitat Quality & Ecosystem Integrity because they directly maintain wetland productivity, improve ecological functioning, and provide critical habitat for fish, birds, and other wildlife. Water quality enhancement and fisheries support were also classified as primary contributors to Socioeconomic benefits, reflecting their direct influence on commercial and recreational fisheries, water quality, recreation, and other benefits that support local communities. Shoreline protection was identified as the primary linkage to Coastal Hazard Risk Reduction because saltmarsh vegetation stabilizes sediments, reduces wave energy, and helps limit shoreline erosion and flooding during storms. Carbon storage and sequestration was classified as the primary linkage to Climate Mitigation, reflecting the globally recognized role of tidal wetlands as efficient long-term blue carbon ecosystems. In contrast, nutrient cycling was classified as a secondary contribution to Climate Mitigation because its influence on greenhouse gas regulation is indirect and varies with site conditions and biogeochemical processes. Similarly, habitat provision, nutrient cycling, and shoreline protection were considered secondary contributors to socioeconomic benefits because their societal value is generally realized through improvements in ecosystem condition, enhanced coastal resilience, and the ecosystem services they support.

5.3 Characteristics of a Saltmarsh in Good Ecological Condition

A saltmarsh in good ecological condition is characterized by persistent native vegetation, appropriate hydrologic connectivity, and sufficient elevation and sediment supply to maintain the marsh within its tidal range over time. Plant communities vary naturally with salinity, elevation, and inundation, but healthy marshes generally support abundant vegetation adapted to local conditions, including smooth cordgrass (*Spartina alterniflora*) in lower, more frequently flooded areas and saltmeadow cordgrass (*Spartina patens*) and other marsh species at higher elevations (Hardaway et al., 2021). Dense and

continuous vegetation, supported by well-developed above- and belowground biomass, contributes to marsh structural integrity and persistence (Bilkovic & Mitchell, 2017; Isdell et al., 2021; Turner et al., 2004; Staver et al., 2021). Where invasive *Phragmites australis* threatens native plant communities, vegetation composition and the extent of invasive dominance are also relevant indicators of ecological condition (Hazelton et al., 2014; Kettenring et al., 2012).

Good ecological condition also requires maintaining the spatial integrity and elevation of the marsh platform. Increasing conversion of vegetated marsh to open water can indicate fragmentation and loss, which can be assessed using measures such as the Unvegetated-to-Vegetated Marsh Ratio (UVVR) (Kirwan et al., 2016; Wasson et al., 2019; CBP, 2024).

Long-term persistence also depends on the ability of the marsh surface to remain within the tidal range needed to support marsh vegetation. This requires a balance among sediment deposition, organic matter production, subsidence, and sea-level rise. Healthy marshes therefore need sufficient sediment and organic matter accumulation to maintain their elevation as sea level rises (Kirwan et al., 2016; Raposa et al., 2023). This ability to adjust to changing water levels is an important component of tidal-marsh resilience.

Together, vegetation condition, spatial integrity, marsh elevation, sediment accumulation, and hydrologic connectivity provide evidence of whether a marsh is maintaining the ecological condition needed to sustain its functions over time. These characteristics underpin the marsh's capacity to support habitat, regulate water quality, store carbon, and attenuate waves and erosion.

5.4 Restoration and Management Approaches

Coastal saltmarshes and reedbeds can be conserved, restored, enhanced, or created through a range of Nature-based Solutions (NbS) and supporting restoration and management approaches. These interventions are used to maintain or recover wetland habitat, reduce shoreline erosion and flooding, improve water quality, and help marshes adapt to sea-level rise and land subsidence (Schieder et al., 2018; Kirwan et al., 2016; Wasson et al., 2019). The appropriate approach depends on existing marsh condition, site characteristics, sediment availability, tidal and hydrologic conditions, and the desired NbS outcomes.

Several complementary approaches are commonly used in Chesapeake Bay tidal wetlands:

Marsh restoration and hydrologic reconnection. Restoration seeks to recover ecological condition and function within existing or historically altered wetlands. Common approaches include restoring tidal exchange, controlling invasive species, and adding sediment to marsh surfaces that have lost elevation (Burdick et al., 2017; Piercy et al., 2023; Raposa et al., 2023). Marsh creation, in contrast, establishes new wetland habitat where marsh does not currently exist, often by constructing a suitable elevation platform and allowing or supporting the establishment of tidal-marsh vegetation (Sudol et al., 2020; Staver et al., 2021; Whitfield et al., 2022). Marsh enhancement modifies an existing marsh or its edge to strengthen particular functions, such as shoreline stabilization or resilience to erosion and sea-level rise (Hardaway et al., 2021; Bilkovic & Mitchell, 2017; Isdell et al., 2021). In practice, these approaches are often combined rather than implemented as separate activities.

Marsh creation and living shorelines. Marsh creation establishes tidal wetland habitat where marsh is absent by creating suitable elevations and supporting the establishment of marsh vegetation (Sudol et al., 2020; Staver et al., 2021; Whitfield et al., 2022). Along eroding shorelines, created or restored fringing marshes may be incorporated into living shoreline systems, sometimes with low-profile structural elements such as stone sills where additional wave attenuation or sediment stabilization is required (Bilkovic et al., 2016; Hardaway et al., 2021; Bilkovic & Mitchell, 2017). In Virginia, state law directs the Virginia Marine Resources Commission to permit living-shoreline approaches unless the best available science demonstrates that they are unsuitable, and to incorporate living-shoreline elements to the maximum extent possible when another approach is necessary.

Thin-layer sediment placement and beneficial use of dredged material. Thin-layer placement (TLP) adds suitable sediment to existing marsh surfaces to increase elevation and help maintain vegetation within an appropriate tidal range. Application depth and placement should be determined by existing elevation, vegetation, sediment characteristics, and site-specific elevation needs rather than a single prescribed thickness (Piercy et al., 2023; Raposa et al., 2023). Beneficial use of dredged material can similarly support marsh restoration, enhancement, or creation by supplying sediment to elevation-deficient marshes or constructing new wetland platforms.

Invasive species management. Control of invasive *Phragmites australis* may support restoration where invasive populations have displaced native marsh vegetation. Management can include targeted herbicide application, cutting, or other mechanical methods, followed by monitoring and, where necessary, re-establishment of native vegetation. Because removal alone does not necessarily recover ecosystem conditions, success should be evaluated in terms of native vegetation recovery and restoration of associated wetland processes rather than *Phragmites* removal alone (Hazelton et al., 2014; Kettenring et al., 2012; Rohal et al., 2023). *Phragmites*-dominated marshes can nonetheless provide comparable or greater carbon sequestration and sediment accumulation than native marsh, so management decisions should weigh these benefits against habitat outcomes (Campbell & Campbell, 2026).

Regardless of the approach used, restoration success depends on whether interventions recover and maintain the vegetation, hydrology, sediment processes, elevation, and spatial integrity required for marsh persistence. Restoration activities should therefore be evaluated not only by whether an intervention was implemented, but by whether the marsh is developing the ecological condition and functional capacity when compared to local reference marshes sharing similar tidal and inundation parameters needed to sustain its intended NbS outcomes.

5.5 Performance Indicators and Metrics

Based on a review of the scientific literature and practitioner knowledge, we identified a set of ecological condition characteristics, functional pathways, ecosystem services, and associated benefits through which coastal saltmarshes and reedbeds contribute to NbS outcomes in the Chesapeake Bay. These were organized across the framework's four broader outcome dimensions: Habitat Quality & Ecosystem Integrity, Climate Mitigation, Coastal Hazard Risk Reduction, and Socioeconomic Benefits. Within Habitat Quality & Ecosystem Integrity, the framework distinguishes environmental conditions supporting marsh persistence from measures of vegetation condition and spatial integrity and the

ecological functions supported by healthy marshes, including primary production, nutrient cycling, habitat support, and fisheries support. Climate mitigation is represented through carbon storage and sequestration, while coastal hazard risk reduction is represented through wave and storm-surge attenuation, sediment and shoreline stabilization, and flood reduction. Socioeconomic benefits capture the downstream value of these services through measures such as avoided damages and protection of property and infrastructure. For each pathway, performance indicators and associated metrics provide evidence of ecosystem condition, functional capacity, service delivery, and, where appropriate, resulting societal benefits. This structure enables practitioners to evaluate whether restored marshes are developing and maintaining the ecological capacity needed to sustain their intended NbS outcomes. The indicators are listed in Table 7.

Table 7. Performance indicators and metrics for coastal saltmarsh and reedbed restoration monitoring, organized by NbS outcome dimension and function–service pathway.

Function–service pathway	Performance indicator	Metric (unit)
Habitat Quality & Ecosystem Integrity		
Environmental conditions supporting marsh recovery and persistence	Salinity regime	Soil porewater salinity (PSU)
	Elevation	Relative tidal elevation (Z); elevation change rate (Ec)
	Tidal regime (inundation duration)	Duration of tidal inundation per tidal cycle or per day (h cycle^{-1} or % time inundated)
	Tidal regime (inundation range)	Range of water levels across tidal cycles (m or cm)
	Maximum inundation extent	Spatial extent of marsh surface inundated at peak tide (ha or m^2)
	Maximum inundation depth	Depth of water over marsh surface at peak inundation (m or cm)
	Vertical sediment accretion rate	Accretion rate from surface elevation tables (SETs) paired with marker horizons (mm yr^{-1})
	Micro-horizon elevation and sediment tracking (developmental, charrette-proposed)	Simultaneous elevation change and sediment accretion at sub-annual resolution (mm yr^{-1})
Marsh condition and structural integrity	Vegetated extent and cover	Vegetated area (m^2 or ha); vegetative cover (%)
	Marsh spatial integrity (scoping tool)	Unvegetated-to-vegetated marsh ratio (UVVR)
	Canopy structure and density	Vegetation height (cm); stem density (stems m^{-2})
	Vegetation biomass	Aboveground dry weight (g m^{-2}); belowground or root–rhizome dry weight (g m^{-2})
	Plant community composition and diversity	Desired or native species diversity (Shannon index)
Primary production and nutrient cycling	Primary productivity	Net aboveground primary productivity (g DW m^{-2} yr^{-1})
	Denitrification	Sediment denitrification rate or capacity (mg N m^{-2} d^{-1})
Water-quality regulation	Nutrient retention	Total N retained per unit area (g N m^{-2} or kg N ha^{-1} yr^{-1}); total P retained (g P m^{-2} or kg P ha^{-1} yr^{-1})
	Suspended sediment retention	Suspended sediment retention rate (g m^{-2} d^{-1})

Function–service pathway	Performance indicator	Metric (unit)
	Water clarity / suspended sediments	Suspended sediment concentration (mg L^{-1}); TSS (mg L^{-1}); turbidity (NTU)
Habitat and fisheries support	Nekton community	Fish and crustacean species richness (count); abundance (individuals m^{-2})
	Juvenile fish and crustacean abundance	Juvenile density of key species (individuals m^{-2})
Climate Mitigation		
Carbon storage and sequestration	Soil carbon stock	Soil organic carbon stock to a standardized depth (kg C m^{-2} or Mg C ha^{-1})
	Carbon burial	Carbon burial rate (g C m^{-2} yr^{-1})
	Net ecosystem carbon balance	Net ecosystem production or net ecosystem carbon balance (g C m^{-2} yr^{-1})
Coastal Hazard Risk Reduction		
Wave attenuation and shoreline stabilization	Wave attenuation	Wave-height reduction per unit marsh width (% or m m^{-1}); incident-to-transmitted wave-energy reduction (%)
	Shoreline stabilization	Marsh-edge position change rate (m yr^{-1})
Storm-surge and flood attenuation	Storm-surge attenuation	Reduction in peak water level across the marsh during storm events (cm or m)
	Flood inundation	Maximum inundated area (ha or m^2); maximum inundation depth (m or cm)
Socioeconomic Benefits		
Avoided damages and asset protection	Avoided storm damages	Avoided financial loss per storm event ($); avoided structural damage costs ($)
	Avoided infrastructure damages	Avoided repair expenditures for adjacent roads, utilities, and other infrastructure ($)
	Property protection	Number of residential parcels or length of private waterfront protected from critical erosion thresholds

6. Reading the Results in Context: Scale, Landscape, and a Changing Baseline

Interpreting biophysical trends requires consideration of the scale, configuration, and spatial context of the restoration intervention. The size and geometry of a restoration footprint can influence its capacity to establish, persist, and support self-reinforcing ecological processes (Allen et al., 2011; Schulte et al., 2009). Larger or more contiguous areas may enhance habitat connectivity, facilitate recruitment and recolonization, or increase resilience to environmental stress, whereas smaller or fragmented restoration areas may be more strongly influenced by conditions beyond the project boundary.

Restoration performance is also shaped by the surrounding landscape and watershed. Land use, watershed hydrology, sediment supply, water quality, shoreline development, and connectivity to adjacent habitats can either support or constrain ecological recovery. Consequently, similar interventions may follow different trajectories across sites. A restored marsh or SAV meadow, for example, may show limited establishment or persistence where nutrient enrichment, poor water quality, altered hydrology, or sediment limitation constrain ecosystem development. Such outcomes should therefore be interpreted in relation to both the restoration intervention and the broader environmental conditions in which it operates (Allen et al., 2011; Schulte et al., 2009; Colden et al., 2017). The value of the services a restored site provides also depends on its location relative to the people, properties, and infrastructure that benefit from them: services such as flood prevention, nutrient processing, and wildlife habitat can vary greatly in magnitude across the landscape, largely because of landscape context and the location of beneficiaries (Campbell et al., 2020).

Restoration outcomes must also be evaluated against a changing environmental baseline. Climate change, sea-level rise, shifts in temperature and precipitation, extreme events, and associated changes in physical and chemical conditions can alter ecosystem processes and habitat suitability over the monitoring period. Sea-level rise, for example, can change the elevation and inundation regimes required for marsh persistence, while changes in temperature, salinity, sediment dynamics, and water quality can affect the establishment and survival of SAV and other coastal habitats. A restoration trajectory may therefore reflect both the effects of the intervention and broader environmental change.

These considerations reinforce the importance of distinguishing restoration performance indicators from contextual or enabling environmental variables. Indicators of ecosystem condition, functional capacity, and service delivery provide evidence of whether a restored system is progressing toward its intended outcomes, while contextual variables help explain the environmental conditions under which that trajectory occurs. Where possible, monitoring designs should therefore support interpretation of observed change relative to background variability and broader climate, watershed, land-use, and regional ecosystem trends, particularly when comparing sites or evaluating long-term performance.

A full treatment of landscape-scale processes, regional drivers, and climate attribution is beyond the scope of this framework. Practitioners are therefore encouraged to interpret site-level monitoring alongside regional assessments, watershed information, and relevant climate and environmental projections when evaluating restoration performance.

7. Future Work

This framework focuses on ecosystem condition and the functional capacity needed to sustain ecosystem services. Several needs identified during review are beyond its scope and are priorities for future work:

- Quantifying and valuing ecosystem service flows so that NbS can be included in cost-benefit analyses alongside grey infrastructure.
- Practical guidance on the cost and effort of monitoring each indicator, including the use of literature values or proxy data where in situ data collection is not feasible.
- Case studies applying the framework to Chesapeake Bay restoration and NbS projects.
- A detailed comparison of the framework with the CBP BMP Expert Panel crediting protocols.
- Extension of the framework to additional GET functional groups relevant to the region, such as sandy shorelines and coastal shrublands and grasslands.

References

Allen, S. K., Jr., Brumbaugh, R., Bruce, D., Coen, L. D., Luckenbach, M. W., O'Beirn, F., Paynter, K. T., Powers, S. P., Rheault, R. B., Ross, P. G., Schulte, D. M., Sellner, K. G., & Wesson, J. A. (2011). Restoration goals, quantitative metrics and assessment protocols for evaluating success on restored oyster reef sanctuaries. Report to the Sustainable Fisheries Goal Implementation Team of the Chesapeake Bay Program. Oyster Metrics Workgroup, Chesapeake Bay Program, Annapolis, MD. 57 pp.

do Amaral Camara Lima, M., Bergamo, T. F., Ward, R. D., & Joyce, C. B. (2023). A review of seagrass ecosystem services: providing nature-based solutions for a changing world. Hydrobiologia, 850(12), 2655-2670.

Aoki, L. R., McGlathery, K. J., Wiberg, P. L., Oreska, M. P., Berger, A. C., Berg, P., & Orth, R. J. (2021). Seagrass recovery following marine heat wave influences sediment carbon stocks. Frontiers in Marine Science, 7, 576784.

Ayvazian, S., Mulvaney, K., Zarnoch, C., Palta, M., Reichert-Nguyen, J., McNally, S., ... & Fulweiler, R. W. (2021). Beyond bioextraction: the role of oyster-mediated denitrification in nutrient management. Environmental science & technology, 55(21), 14457-14465.

Baggett, L. P., Powers, S. P., Brumbaugh, R. D., Coen, L. D., DeAngelis, B. M., Greene, J. K., ... & Zu Ermgassen, P. S. (2015). Guidelines for evaluating performance of oyster habitat restoration. Restoration Ecology, 23(6), 737-745.

Baggett, L.P., S.P. Powers, R. Brumbaugh, L.D. Coen, B. DeAngelis, J. Greene, B. Hancock, and S. Morlock. (2014). Oyster habitat restoration monitoring and assessment handbook. The Nature Conservancy, Arlington, VA, USA., 96pp.

Batiuk, R. A., Bergstrom, P., Kemp, W. M., Koch, E., Murray, L., Stevenson, J. C., Bartleson, R., Carter, V., Rybicki, N., Landwehr, J. M., Gallegos, C., Karrh, L., Naylor, M., Wilcox, D., Moore, K. A., Ailstock, S., & Teichberg, M. (2000). Submerged aquatic vegetation habitat requirements and restoration targets: A technical synthesis. U.S. Environmental Protection Agency, Chesapeake Bay Program.

Batiuk, R. A., Bergstrom, P., Moore, K. A., Orth, R. J., & Dennison, W. C. (2000). Chesapeake Bay submerged aquatic vegetation water quality and habitat-based requirements and restoration targets: A second technical synthesis. U.S. Environmental Protection Agency, Chesapeake Bay Program, Annapolis, MD. 210 p. (EPA 903-R-00-014 / CBP/TRS 245/00).

Bilkovic, D. M., & Roggero, M. M. (2008). Effects of coastal development on nearshore estuarine nekton communities. Marine Ecology Progress Series, 358, 27-39.

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.

Bilkovic, D. M., & Mitchell, M. M. (2017). Designing living shoreline salt marsh ecosystems to promote coastal resilience. In Living shorelines (pp. 293-316). CRC Press.

Bilkovic, D. M., Mitchell, M. M., Havens, K. J., & Hershner, C. H. (2019). Chesapeake Bay. In World seas: An environmental evaluation (pp. 379-404). Academic Press.

Bredes, A., Tso, G., Gittman, R. K., Narayan, S., Tomiczek, T., Miller, J. K., & Morris, R. L. (2024). A 20-year systematic review of wave dissipation by soft and hybrid nature-based solutions (NbS). Ecological Engineering, 209, 107418.

Bruce, D. G., Cornwell, J. C., Harris, L., Ihde, T. F., Kellogg, M. L., Knoche, S., ... & Vogt, B. (2021). A synopsis of research on the ecosystem services provided by large-scale oyster restoration in the Chesapeake Bay. NOAA Technical Memorandum NMFS-OHC-8, 52.

Burdick, D. M., Moore, G. E., Peter, C. R., & Wilson, G. M. (2017). Innovative salt marsh restoration techniques for the Great Marsh. Technical Report to the Parker River and Rachel Carson National Wildlife Refuges. University of New Hampshire, Jackson Estuarine Laboratory. 87 pp.

Campbell, A. D., & Wang, Y. (2020). Salt marsh monitoring along the mid-Atlantic coast by Google Earth Engine enabled time series. PloS one, 15(2), e0229605.

Campbell, E., Marks, R., & Conn, C. (2020). Spatial modeling of the biophysical and economic values of ecosystem services in Maryland, USA. Ecosystem Services, 43, 101093. https://doi.org/10.1016/j.ecoser.2020.101093

Campbell, E., & Campbell, A. (2026). The case for and against *Phragmites australis*: An ecosystem service cost–benefit analysis for Chesapeake Bay marshes. Wetlands Ecology and Management, 34, 19. https://doi.org/10.1007/s11273-026-10120-4

Carnegie, R. B., & Burreson, E. M. (2011). Declining impact of an introduced pathogen: Haplosporidium nelsoni in the oyster *Crassostrea virginica* in Chesapeake Bay. Marine Ecology Progress Series, 432, 1-15.

Center for Coastal Resources Management [CCRM]. (2024). ShoreWatch App living shoreline monitoring protocol manual. Virginia Institute of Marine Science, College of William & Mary. Gloucester Point, Virginia. 74 p.

Chesapeake Bay Program. (2024). Collaborative Marsh Adaptation Project final report. https://www.chesapeakebay.net/files/Collaborative-Marsh-Adaptation-Project-Final-Report_Final_08.05.2024-3-1.pdf

Chesapeake Monitoring Cooperative [CMC]. (2021). Chesapeake Bay SAV Watchers Tier 2 monitoring program guide and methods manual. Alliance for the Chesapeake Bay & Chesapeake Monitoring Cooperative. 48 p.

Christianen, M. J., van Belzen, J., Herman, P. M., van Katwijk, M. M., Lamers, L. P., van Leent, P. J., & Bouma, T. J. (2013). Low-canopy seagrass beds still provide important coastal protection services. PloS one, 8(5), e62413.

Coen, L. D., & Luckenbach, M. W. (2000). Developing success criteria and goals for evaluating oyster reef restoration: ecological function or resource exploitation?. Ecological engineering, 15(3-4), 323-343.

Coffin, A. W., Sclater, V., Swain, H., Ponce-Campos, G. E., & Seymour, L. (2021). Ecosystem services in working lands of the southeastern USA. Frontiers in Sustainable Food Systems, 5, 541590.

Colden, A. M., Fall, K. A., Cartwright, G. M., & Friedrichs, C. T. (2016). Sediment suspension and deposition across restored oyster reefs of varying orientation to flow: implications for restoration. Estuaries and Coasts, 39(5), 1435-1448.

Colden, A. M., Latour, R. J., & Lipcius, R. N. (2017). Reef height drives threshold dynamics of restored oyster reefs. Marine Ecology Progress Series, 582, 1-13.

Cornwell, J., Bricker, S., Lacatell, A., Luckenbach, M., Marenghi, F., Moore, C., Parker, M., Paynter, K., Rose, J., Sanford, L., Wolinski, W., Caretti, O. N., Reichert-Nguyen, J., & Slacum, H. W. (2023). Nitrogen and phosphorus reduction associated with harvest of hatchery-produced oysters and reef restoration: Assimilation and enhanced denitrification. Panel recommendations (Oyster BMP Expert Panel Second Incremental Report). Chesapeake Bay Program Partnership Water Quality Goal Implementation Team.

Cornwell, J. C., Owens, M. S., Kellogg, M. L., & Luckenbach, M. W. (2014). Oyster reef denitrification in Choptank River, Chesapeake Bay. Technical Report to the National Oceanic and Atmospheric Administration (NOAA) Chesapeake Bay Office. University of Maryland Center for Environmental Science, Cambridge, MD.

Cornwell, J. C., Owens, M. S., & Staver, L. W. (2022). Nutrient retention and release in eroding Chesapeake bay tidal wetlands. JAWRA Journal of the American Water Resources Association, 58(6), 940-957.

Correll, M., Watson, J., & Wilson, B. (2024). Coastal marsh restoration: An ecosystem approach for the Mid-Atlantic. National Oceanic and Atmospheric Administration (NOAA) & United States Fish and Wildlife Service (USFWS).

Expert Panel on Shoreline Management. (2019). Recommendations of the Expert Panel to define removal rates for shoreline management projects (approved 2015; amended June 2017 and November 2019). Chesapeake Bay Program.

Federal Emergency Management Agency. (2021). Building community resilience with nature-based solutions: A guide for local communities. U.S. Department of Homeland Security. https://des.mt.gov/Mitigation/Mitigation-Documents/fema_riskmap-nature-based-solutions-guide_2021-1.pdf

Fergel, J. R., Isdell, R. E., DiPetto, G., Nunez, K., Gregory, S. T., Hill, E., & Bilkovic, D. M. (2026). The shoreline protection potential of oyster reefs: a systematic review and meta-analysis. Nature-Based Solutions, 100304.

Forrester, J., Leonardi, N., Cooper, J. R., & Kumar, P. (2024). Seagrass as a nature-based solution for coastal protection. Ecological Engineering, 206, 107316.

Fulford, R. S., Breitburg, D. L., Newell, R. I., Kemp, W., & Luckenbach, M. (2007). Effects of oyster population restoration strategies on phytoplankton biomass in Chesapeake Bay: a flexible modeling approach. Marine Ecology Progress Series, 336, 43-61.

Gann, G. D., & Lamb, D. (2006). Ecological restoration: a means of conserving biodiversity and sustaining livelihoods. Arizona: Society for Ecological Restoration International.

Gedan, K. B., & Fernández-Pascual, E. (2019). Salt marsh migration into salinized agricultural fields: A novel assembly of plant communities. Journal of Vegetation Science, 30(5), 1007-1016.

Grabowski, J. H., Brumbaugh, R. D., Conrad, R. F., Keeler, A. G., Opaluch, J. J., Peterson, C. H., ... & Smyth, A. R. (2012). Economic valuation of ecosystem services provided by oyster reefs. Bioscience, 62(10), 900-909.

Greiner, J. T., McGlathery, K. J., Gunnell, J., & McKee, B. A. (2013). Seagrass restoration enhances “blue carbon” sequestration in coastal waters. PloS one, 8(8), e72469.

Grizzetti, B., Liquete, C., Pistocchi, A., Vigiak, O., Zulian, G., Bouraoui, F., ... & Cardoso, A. C. (2019). Relationship between ecological condition and ecosystem services in European rivers, lakes and coastal waters. Science of the Total Environment, 671, 452-465.

Gurbisz, C., & Kemp, W. M. (2014). Unexpected resurgence of a large submersed plant bed in Chesapeake Bay: Analysis of time series data. Limnology and Oceanography, 59(2), 482-494.

Hardaway, C. S., Milligan, D. A., & Duhring, K. (2021). Living shoreline design guidelines for shore protection in Virginia’s estuarine environment.

Hardaway Jr, C. S., & Duhring, K. (2010). Living Shoreline Design Guidelines for Shore Protection in Virginia's Estuarine Environments.

Harwell, H. D., Kingsley-Smith, P. R., Kellogg, M. L., Allen, S. M., Allen, S. K., Meritt, D. W., ... & Luckenbach, M. W. (2010). A comparison of *Crassostrea virginica* and C. ariakensis in Chesapeake Bay: does oyster species affect habitat function?. Journal of Shellfish Research, 29(2), 253-269.

Hazelton, E. L., Mozdzer, T. J., Burdick, D. M., Kettenring, K. M., & Whigham, D. F. (2014). *Phragmites australis* management in the United States: 40 years of methods and outcomes. AoB plants, 6, plu001.

Hendriks, I. E., Olsen, Y. S., Ramajo, L., Basso, L., Steckbauer, A., Moore, T. S., & Duarte, C. M. (2014). Photosynthetic activity buffers ocean acidification in seagrass meadows. Biogeosciences, 11(2), 333-346.

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.

IUCN (2026). IUCN Global Standard for Nature-based Solutions™. A user-friendly framework for assessing, implementing, and monitoring scalable, high-integrity NbS. Second Edition. IUCN.

Jasinski, D., Gurbisz, C., Huey, L., and B. Landry. (2021). Small-scale SAV Restoration in Chesapeake Bay: A Guide to the Restoration of Submerged Aquatic Vegetation (SAV) in Chesapeake Bay and its Tidal Tributaries. Approved by the CBP SAV Workgroup in October 2021. Available at chesapeakebay. net

Jänes, H., Macreadie, P. I., Zu Ermgassen, P. S. E., Gair, J. R., Treby, S., Reeves, S., Nicholson, E., Ierodiaconou, D., & Carnell, P. (2020). Quantifying fisheries enhancement from coastal vegetated ecosystems. Ecosystem Services, 43, 101105.

Jones, L., Anderson, S., Læssøe, J., Banzhaf, E., Jensen, A., Bird, D. N., ... & Zandersen, M. (2022). A typology for urban Green Infrastructure to guide multifunctional planning of nature-based solutions. Nature-Based Solutions, 2, 100041.

van Katwijk, M. M., Thorhaug, A., Marbà, N., Orth, R. J., Duarte, C. M., Kendrick, G. A., ... & Verduin, J. J. (2016). Global analysis of seagrass restoration: the importance of large-scale planting. Journal of Applied Ecology, 53(2), 567-578.

Keith, D. A., Ferrer-Paris, J. R., Nicholson, E., & Kingsford, R. T. (2020). IUCN Global Ecosystem Typology 2.0: Descriptive profiles for biomes and ecosystem functional groups.

Kellogg, M. L., Cornwell, J. C., Owens, M. S., & Paynter, K. T. (2013). Denitrification and nutrient assimilation on a restored oyster reef. Marine Ecology Progress Series, 480, 1-19.

Kemp, W. M., Bartleson, R., Bergstrom, P., Carter, V., Gallegos, C. L., Hunley, W., ... & Wilcox, D. J. (2004). Habitat requirements for submerged aquatic vegetation in Chesapeake Bay: Water quality, light regime, and physical-chemical factors. Estuaries, 27(3), 363–377.

Kettenring, K. M., de Blois, S., & Hauber, D. P. (2012). Moving from a regional to a continental perspective of *Phragmites australis* invasion in North America. AoB plants, 2012, pls040.

Kirwan, M. L., Langley, J. A., Guntenspergen, G. R., & Megonigal, J. P. (2013). The impact of sea-level rise on organic matter decay rates in Chesapeake Bay brackish tidal marshes. Biogeosciences, 10(3), 1869-1876.

Kirwan, M. L., Temmerman, S., Skeehan, E. E., Guntenspergen, G. R., & Fagherazzi, S. (2016). Overestimation of marsh vulnerability to sea level rise. Nature Climate Change, 6(3), 253-260.

Kurth, M. H., Piercy, C. D., Jackson, C. R., Lemasson, B. H., & Harris, B. D. (2024). Life cycle management of natural infrastructure: assessment of state of practice and current tools. Frontiers in Built Environment, 9, 1181835.

Landry, B., Trice, M., & Robertson, T. (2020). Chesapeake Bay SAV Watchers Field Guide and Monitoring Protocol Manual: Tier II Citizen Science Monitoring. Maryland Department of Natural Resources & Chesapeake Bay Program SAV Workgroup, Annapolis, MD.

Landry, B., and Golden, B. (2026). Submerged Aquatic Vegetation Mitigation and Monitoring Guidance for the Chesapeake and Atlantic Coastal Bays. Developed by the Chesapeake Bay Program's SAV Workgroup for regulatory agencies overseeing SAV mitigation in the Chesapeake and Atlantic Coastal Bays

Larsen, C., Clark, I. E., Guntenspergen, G., Cahoon, D., Caruso, V., Hupp, C., & Yanosky, T. (2004). The Blackwater NWR Inundation Model. Rising sea level on a low-lying coast: land use planning for wetlands (No. 2004-1302).

Lefcheck, J. S., Wilcox, D. J., Murphy, R. R., Marion, S. R., & Orth, R. J. (2017). Multiple stressors threaten the imperiled coastal foundation species eelgrass (*Zostera marina*) in Chesapeake Bay, USA. Global Change Biology, 23(9), 3474-3483.

Lefcheck, J. S., Orth, R. J., Dennison, W. C., Wilcox, D. J., Murphy, R. R., Keisman, J., ... & Batiuk, R. A. (2018). Long-term nutrient reductions lead to the unprecedented recovery of a temperate coastal region. Proceedings of the National Academy of Sciences, 115(14), 3658-3662.

Mace, G. M., Hails, R. S., Cryle, P., Harlow, J., & Clarke, S. J. (2015). Towards a risk register for natural capital. Journal of Applied Ecology, 52(3), 641-653.

Makowska, A., Kharadi, N., Kuyer, J., Tinch, R., English, D., Hull., S., Armstrong, S., Middleton, A., Baruah, L., Beaumont, N., Molloy, L., Morgan, V., Merayo, E., Judd, A. & Proudfoot, R. 2022. Review of approaches for the assessment of marine Natural Capital in the context of UK marine environmental policy and management. JNCC Report No.702, JNCC, Peterborough, ISSN 0963-8091.

Marion, S. R., & Orth, R. J. (2010). Innovative techniques for large-scale seagrass restoration using *Zostera marina* (eelgrass) seeds. Restoration Ecology, 18(4), 514-526.

Mitchell, M., Herman, J., Bilkovic, D. M., & Hershner, C. (2017). Marsh persistence under sea-level rise is controlled by multiple, geologically variable stressors. Ecosystem Health and Sustainability, 3(10), 1379888.

Mitchell, M., & Bilkovic, D. M. (2019). Embracing dynamic design for climate-resilient living shorelines. Journal of Applied Ecology, 56(5), 1099-1105.

Moore, K. A., Wilcox, D. J., & Orth, R. J. (2000). Analysis of the abundance of submersed aquatic vegetation communities in the Chesapeake Bay. Estuaries, 23(1), 115-127.

Moore, K. A., Shields, E. C., & Parrish, D. B. (2014). Impacts of varying estuarine temperature and light conditions on *Zostera marina* (eelgrass) and its interactions with *Ruppia maritima* (widgeongrass). Estuaries and Coasts, 37(Suppl 1), 20-30.

National Oceanic and Atmospheric Administration [NOAA]. (2026). Implementation monitoring: Guidance for proposing and conducting Tier 1 monitoring. NOAA Restoration Center, Updated April 2026. 28 p.

Neubauer, S. C., Anderson, I. C., Constantine, J. A., & Kuehl, S. A. (2002). Sediment deposition and accretion in a mid-Atlantic (USA) tidal freshwater marsh. Estuarine, Coastal and Shelf Science, 54(4), 713-727.

Neubauer, S. C., Anderson, I. C., & Neikirk, B. B. (2005). Nitrogen cycling and ecosystem exchanges in a Virginia tidal freshwater marsh. Estuaries, 28(6), 909-922.

Newell, R. I., & Koch, E. W. (2004). Modeling seagrass density and distribution in response to changes in turbidity stemming from bivalve filtration and seagrass sediment stabilization. Estuaries, 27(5), 793-806.

Newell, R. I., Fisher, T. R., Holyoke, R. R., & Cornwell, J. C. (2005). Influence of eastern oysters on nitrogen and phosphorus regeneration in Chesapeake Bay, USA. In The Comparative Roles of Suspension-Feeders in Ecosystems: Proceedings of the NATO Advanced Research Workshop on The Comparative Roles of Suspension-Feeders in Ecosystems Nida, Lithuania 4–9 October 2003 (pp. 93-120). Dordrecht: Springer Netherlands.

Nordlund, L. M., Jackson, E. L., Nakaoka, M., Samper-Villarreal, J., Beca-Carretero, P., & Creed, J. C. (2018). Seagrass ecosystem services–What's next?. Marine pollution bulletin, 134, 145-151.

Obst, C., Hein, L., & Edens, B. (2016). National accounting and the valuation of ecosystem assets and their services. Environmental and Resource Economics, 64(1), 1-23.

Olander, L., Warnell, K., Mason, S., Wilson, A., & Jones-Farrand, T. (2025). Improving evaluation of coastal NBS effectiveness for hazard attenuation and biodiversity. Nicholas Institute for Energy, Environment & Sustainability, Duke University.

Oreska, M. P., McGlathery, K. J., Aoki, L. R., Berger, A. C., Berg, P., & Mullins, L. (2020). The greenhouse gas offset potential from seagrass restoration. Scientific reports, 10(1), 7325.

Orth, R. J., Nowak, J. F., Wilcox, D. J., Whiting, J. R., & Nagey, L. S. (1998). Distribution of submerged aquatic vegetation in the Chesapeake Bay and tributaries and the coastal bays-1997 (Special Scientific Report No. 138). Virginia Institute of Marine Science.

Orth, R. J., Williams, M. R., Marion, S. R., Wilcox, D. J., Carruthers, T. J., Moore, K. A., ... & Batiuk, R. A. (2010). Long-term trends in submersed aquatic vegetation (SAV) in Chesapeake Bay, USA, related to water quality. Estuaries and coasts, 33(5), 1144-1163.

Orth, R. J., Dennison, W. C., Lefcheck, J. S., Gurbisz, C., Hannam, M., Keisman, J., ... & Wilcox, D. J. (2017a). Submersed aquatic vegetation in Chesapeake Bay: sentinel species in a changing world. Bioscience, 67(8), 698-712.

Orth, R. J., Dennison, W. C., Lefebvre, A., Moore, K. E., Nanjappa, S., Santoro, M. A., ... & Wilcox, D. J. (2017b). Chesapeake Bay submerged aquatic vegetation (SAV): A third technical synthesis. Approved by the CBP SAV Workgroup. Chesapeake Bay Program. 140 p.

Orth, R. J., Lefcheck, J. S., McGlathery, K. S., Aoki, L., Luckenbach, M. W., Moore, K. A., ... & Lusk, B. (2020). Restoration of seagrass habitat leads to rapid recovery of coastal ecosystem services. Science advances, 6(41), eabc6434.

Parker, M., & Bricker, S. (2020). Sustainable oyster aquaculture, water quality improvement, and ecosystem service value potential in Maryland Chesapeake Bay. Journal of Shellfish Research, 39(2), 269-281.

Piercy, C. D., Welp, T. L., & Mohan, R. K. (2023). Guidelines for how to approach thin-layer placement projects. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Raposa, K. B., Woolfolk, A., Endris, C. A., Fountain, M. C., Moore, G., Tyrrell, M., ... & 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.

Rodney, W. S., & Paynter, K. T. (2006). Comparisons of macrofaunal assemblages on restored and non-restored oyster reefs in mesohaline regions of Chesapeake Bay in Maryland. Journal of Experimental Marine Biology and Ecology, 335(1), 39-51.

Rohal, C. B., Hazelton, E. L., McFarland, E. K., Downard, R., McCormick, M. K., Whigham, D. F., & Kettenring, K. M. (2023). Landscape and site factors drive invasive *Phragmites* management and native plant recovery across Chesapeake Bay wetlands. Ecosphere, 14(1), e4392.

Schaffler, J. J., Montfrans, J., Jones, C. M., & Orth, R. J. (2013). Fish species distribution in seagrass habitats of Chesapeake Bay are structured by abiotic and biotic factors. Marine and Coastal Fisheries, 5(1), 114-124.

Schieder, N. W., Walters, D. C., & Kirwan, M. L. (2018). Massive upland to wetland conversion compensated for historical marsh loss in Chesapeake Bay, USA. Estuaries and coasts, 41(4), 940-951.

Schulte, D. M., Burke, R. P., & Lipcius, R. N. (2009). Unprecedented restoration of a native oyster metapopulation. Science, 325(5944), 1124-1128.

Smith, R. S., Cheng, S. L., & Castorani, M. C. (2023). Meta-analysis of ecosystem services associated with oyster restoration. Conservation Biology, 37(1), e13966.

Sowińska-Świerkosz, B., & García, J. (2022). What are Nature-based solutions (NBS)? Setting core ideas for concept clarification. Nature-Based Solutions, 2, 100009.

Staver, L. W., Cornwell, J. C., Nidzieko, N. J., Staver, K. W., Stevenson, J. C., Owens, M., ... & Lopez-Gonzalez, L. (2021). The fate of nitrogen in dredged material used for tidal marsh restoration. Journal of Marine Science and Engineering, 9(8), 849.

Stroud, H. M., Kirshen, P. H., & Timmons, D. (2023). Monetary evaluation of co-benefits of nature-based flood risk reduction infrastructure to promote climate justice. Mitigation and Adaptation Strategies for Global Change, 28(1), 5.

Sudol, T. A., Noe, G. B., & Reed, D. J. (2020). Tidal wetland resilience to increased rates of sea level rise in the Chesapeake Bay: Introduction to the special feature. Wetlands, 40(6), 1667-1671.

Tango, P., Landry, B. J., Trice, M., Sullivan, B. M., Robertson, T., & Dennison, W. C. (2026). Advancing monitoring approaches to enhance tidal Chesapeake Bay habitat assessment for submerged aquatic vegetation, water clarity, chlorophyll a and dissolved oxygen.

The Nature Conservancy (TNC). (2021). The Blue Guide to coastal resilience: Protecting coastal communities through nature-based solutions. A handbook for practitioners of disaster risk reduction. The Nature Conservancy

Turner, J. S., Friedrichs, C. T., Parrish, D. B., & Fall, K. A. (2025). Chesapeake Bay Water Clarity: Challenges and Successes. Annual Review of Marine Science, 18.

Turner, R. E., Swenson, E. M., Milan, C. S., Lee, J. M., & Oswald, T. A. (2004). Below-ground biomass in healthy and impaired salt marshes. Ecological Research, 19(1), 29-35.

United Nations. (2021). System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA EA). Department of Economic and Social Affairs, United Nations Statistics Division. New York, NY.

Unsworth, R. K., Nordlund, L. M., & Cullen-Unsworth, L. C. (2019). Seagrass meadows support global fisheries production. Conservation Letters, 12(1), e12566.

Vouk, I., Pilechi, V., Provan, M., & Murphy, E. (2021). Nature-based solutions for coastal and riverine flood and erosion risk management. Canadian Standards Association

Waldbusser, G. G., Steenson, R. A., & Green, M. A. (2011). Oyster shell dissolution rates in estuarine waters: effects of pH and shell legacy. Journal of Shellfish Research, 30(3), 659-669.

Wasson, K., Ganju, N. K., Defne, Z., Endris, C., Elsey-Quirk, T., Thorne, K. M., ... & Raposa, K. B. (2019). Understanding tidal marsh trajectories: evaluation of multiple indicators of marsh persistence. Environmental Research Letters, 14(12), 124073.

Waylen, K. A., Wilkinson, M. E., Blackstock, K. L., & Bourke, M. (2024). Nature-based solutions and restoration are intertwined but not identical: Highlighting implications for societies and ecosystems. Nature-Based Solutions, 5, 100116.

Whitfield, P.E., J.L. Davis, A.S. Tritinger, D.M. Szimanski, R.R Golden, J.Z. Gailani, M.T. Ramirez, B.D. Herman, M. Whitbeck and J.K. King. 2022. Swan Island: Monitoring and Adaptive Management Plan. Report ERDC TR-22-14. Vicksburg, MS, USA: US Army Corps of Engineers - Engineer Research and Development Center (USA)

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. 31108). National Bureau of Economic Research.

Appendix A. Literature Reviewed

References were classified by ecosystem typology (Seagrass Meadows, Oyster Beds and Reefs, and Coastal Saltmarshes and Reedbeds) using Google Gemini and verified by co-authors.

Reference	Seagrass meadows	Oyster beds and reefs	Coastal saltmarshes and reedbeds
Allen, S. K., Jr., et al. (2011). Restoration goals, quantitative metrics and assessment protocols for evaluating success on restored oyster reef sanctuaries.		X	
Aoki, L. R., et al. (2021). Seagrass recovery following marine heat wave influences sediment carbon stocks.	X		
Ayvazian, S., et al. (2021). Beyond bioextraction: the role of oyster-mediated denitrification in nutrient management.		X	
Baggett, L. P., et al. (2015). Guidelines for evaluating performance of oyster habitat restoration.		X	
Baggett, L. P., et al. (2014). Oyster habitat restoration monitoring and assessment handbook.		X	
Bilkovic, D. M., & Roggero, M. M. (2008). Effects of coastal development on nearshore estuarine nekton communities.		X	X
Bilkovic, D. M., et al. (2016). The role of living shorelines as estuarine habitat conservation strategies.			X
Bredes, A., et al. (2024). A 20-year systematic review of wave dissipation by soft and hybrid nature-based solutions (NbS).	X	X	X
Bruce, D. G., et al. (2021). A synopsis of research on the ecosystem services provided by large-scale oyster restoration in the Chesapeake Bay.		X	
Burdick, D. M., et al. (2017). Innovative salt marsh restoration techniques for the Great Marsh.			X
Campbell, A. D., & Wang, Y. (2020). Salt marsh monitoring along the mid-Atlantic coast by Google Earth Engine enabled time series.			X
Carnegie, R. B., & Burreson, E. M. (2011). Declining impact of an introduced pathogen: Haplosporidium nelsoni in the oyster *Crassostrea virginica* in Chesapeake Bay.		X	
Center for Coastal Resources Management [CCRM]. (2024). ShoreWatch App living shoreline monitoring protocol manual.		X	X
Chesapeake Monitoring Cooperative [CMC]. (2021). Chesapeake Bay SAV Watchers Tier 2 monitoring program guide and methods manual.	X		
Christianen, M. J., et al. (2013). Low-canopy seagrass beds still provide important coastal protection services.	X		
Coen, L. D., & Luckenbach, M. W. (2000). Developing success criteria and goals for evaluating oyster reef restoration: ecological function or resource exploitation?		X	
Colden, A. M., et al. (2016). Sediment suspension and deposition across restored oyster reefs of varying orientation to flow: implications for restoration.		X	
Colden, A. M., et al. (2017). Reef height drives threshold dynamics of restored oyster reefs.		X	
Cornwell, J. C., et al. (2022). Nutrient retention and release in eroding Chesapeake bay tidal wetlands.			X

Reference	Seagrass meadows	Oyster beds and reefs	Coastal saltmarshes and reedbeds
Cornwell, J. C., et al. (2014). Oyster reef denitrification in Choptank River, Chesapeake Bay.		X	
Correll, M., et al. (2024). Coastal marsh restoration: An ecosystem approach for the Mid-Atlantic.			X
do Amaral Camara Lima, M., et al. (2023). A review of seagrass ecosystem services: providing nature-based solutions for a changing world.	X		
Federal Emergency Management Agency. (2021). Building community resilience with nature-based solutions: A guide for local communities.		X	X
Fergel, J. R., et al. (2026). The shoreline protection potential of oyster reefs: a systematic review and meta-analysis.		X	
Forrester, J., et al. (2024). Seagrass as a nature-based solution for coastal protection.	X		
Fulford, R. S., et al. (2007). Effects of oyster population restoration strategies on phytoplankton biomass in Chesapeake Bay.		X	
Gedan, K. B., & Fernández-Pascual, E. (2019). Salt marsh migration into salinized agricultural fields.			X
Greiner, J. T., et al. (2013). Seagrass restoration enhances “blue carbon” sequestration in coastal waters.	X		
Hardaway, C. S., et al. (2021). Living shoreline design guidelines for shore protection in Virginia’s estuarine environment.		X	X
Harwell, H. D., et al. (2010). A comparison of *Crassostrea virginica* and C. ariakensis in Chesapeake Bay.		X	
Hazelton, E. L., et al. (2014). *Phragmites australis* management in the United States: 40 years of methods and outcomes.			X
Hendriks, I. E., et al. (2014). Photosynthetic activity buffers ocean acidification in seagrass meadows.	X		
Isdell, R. E., et al. (2021). Living shorelines achieve functional equivalence to natural fringe marshes across multiple ecological metrics.		X	X
Jänes, H., et al. (2020). Quantifying fisheries enhancement from coastal vegetated ecosystems.	X		
Kellogg, M. L., et al. (2013). Denitrification and nutrient assimilation on a restored oyster reef.		X	
Kettenring, K. M., et al. (2012). Moving from a regional to a continental perspective of *Phragmites australis* invasion in North America.			X
Kirwan, M. L., et al. (2013). The impact of sea-level rise on organic matter decay rates in Chesapeake Bay brackish tidal marshes.			X
Kirwan, M. L., et al. (2016). Overestimation of marsh vulnerability to sea level rise.			X
Landry, B., & Golden, B. (2026). Submerged Aquatic Vegetation Mitigation and Monitoring Guidance for the Chesapeake and Atlantic Coastal Bays.	X		
Landry, B., et al. (2020). Chesapeake Bay SAV Watchers Field Guide and Monitoring Protocol Manual.	X		
Larsen, C., et al. (2004). The Blackwater NWR Inundation Model.			X
Mitchell, M., & Bilkovic, D. M. (2019). Embracing dynamic design for climate-resilient living shorelines.			X

Reference	Seagrass meadows	Oyster beds and reefs	Coastal saltmarshes and reedbeds
Mitchell, M., et al. (2017). Marsh persistence under sea-level rise is controlled by multiple, geologically variable stressors.			X
Moore, K. A., et al. (2014). Impacts of varying estuarine temperature and light conditions on *Zostera marina* (eelgrass) and its interactions with *Ruppia maritima* (widgeongrass).	X		
Moore, K. A., et al. (2000). Analysis of the abundance of submersed aquatic vegetation communities in the Chesapeake Bay.	X		
National Oceanic and Atmospheric Administration [NOAA]. (2026). Implementation monitoring: Guidance for proposing and conducting Tier 1 monitoring.		X	X
Neubauer, S. C., et al. (2005). Nitrogen cycling and ecosystem exchanges in a Virginia tidal freshwater marsh.			X
Neubauer, S. C., et al. (2002). Sediment deposition and accretion in a mid-Atlantic (USA) tidal freshwater marsh.			X
Newell, R. I., & Koch, E. W. (2004). Modeling seagrass density and distribution in response to changes in turbidity.	X		
Newell, R. I., et al. (2005). Influence of eastern oysters on nitrogen and phosphorus regeneration in Chesapeake Bay.		X	
Nordlund, L. M., et al. (2018). Seagrass ecosystem services–What's next?	X		
Oreska, M. P., et al. (2020). The greenhouse gas offset potential from seagrass restoration.	X		
Orth, R. J., et al. (1998). Distribution of submerged aquatic vegetation in the Chesapeake Bay and tributaries and the coastal bays.	X		
Parker, M., & Bricker, S. (2020). Sustainable oyster aquaculture, water quality improvement, and ecosystem service value potential in Maryland Chesapeake Bay.		X	
Piercy, C., et al. (2023). Guidelines for How to Approach Thin-Layer Placement Projects.			X
Raposa, K. B., et al. (2023). Evaluating thin-layer sediment placement as a tool for enhancing tidal marsh resilience.			X
Rodney, W. S., & Paynter, K. T. (2006). Comparisons of macrofaunal assemblages on restored and non-restored oyster reefs in mesohaline regions of Chesapeake Bay.		X	
Rohal, C. B., et al. (2023). Landscape and site factors drive invasive *Phragmites*			X
management and native plant recovery across Chesapeake Bay wetlands.			
Schieder, N. W., et al. (2018). Massive upland to wetland conversion compensated for historical marsh loss in Chesapeake Bay, USA.			X
Schulte, D. M., et al. (2009). Unprecedented restoration of a native oyster metapopulation.		X	
Smith, R. S., et al. (2023). Meta-analysis of ecosystem services associated with oyster restoration.		X	
Staver, L. W., et al. (2021). The fate of nitrogen in dredged material used for tidal marsh restoration.			X
Sudol, T. A., et al. (2020). Tidal wetland resilience to increased rates of sea level rise in the Chesapeake Bay.			X

Reference	Seagrass meadows	Oyster beds and reefs	Coastal saltmarshes and reedbeds
Tango, P., et al. (2026). Advancing monitoring approaches to enhance tidal Chesapeake Bay habitat assessment for submerged aquatic vegetation, water clarity, chlorophyll a and dissolved oxygen.	X		
The Nature Conservancy (TNC). (2021). The Blue Guide to coastal resilience.	X	X	X
Turner, R. E., et al. (2004). Below-ground biomass in healthy and impaired salt marshes.			X
Vouk, I., et al. (2021). Nature-based solutions for coastal and riverine flood and erosion risk management.			X
Waldbusser, G. G., et al. (2011). Oyster shell dissolution rates in estuarine waters: effects of pH and shell legacy.		X	
Wasson, K., et al. (2019). Understanding tidal marsh trajectories: evaluation of multiple indicators of marsh persistence.			X
Whitfield, P.E., et al. (2022). Swan Island: Monitoring and Adaptive Management Plan.			X

Appendix B. Charrette Summary: Main Takeaways for Ecosystem Services, Performance Indicators, and Metrics

This appendix presents a synthesis of stakeholder feedback, technical breakout discussions, and expert consensus gathered during the First and Second Charrettes held in 2026. This summary highlights key takeaways, practical concerns, and scientific justifications that provide the rationale for framework decisions related to the ecosystem services, performance indicators, and metrics sections of the document. This summary was synthesized from raw notes using Gemini, with subsequent expert review and revisions by the co-authors to ensure scientific accuracy and alignment with stakeholder consensus.

Seagrass meadows

- **Distinguishing Environmental Suitability from Performance.** Poor water clarity typically represents a cause of restoration failure rather than an outcome of the intervention itself. **Framework decision:** divide enabling environmental conditions (e.g., light availability, nutrients, and water clarity) from Meadow condition and structural integrity indicators (e.g., extent, shoot density, and canopy height).
- **Aboveground vs. Belowground Biomass.** Experts noted that while aboveground vegetation is highly feasible to measure, belowground biomass is a much more robust predictor of a meadow's long-term sustainability. However, belowground monitoring was acknowledged to have low feasibility due to labor-intensive sampling. **Framework decision:** include both aboveground and belowground dry weight metrics under the structural integrity section, allowing practitioners to choose metrics based on their specific monitoring capacity.
- **Evaluating Habitat and Fisheries Support Pathways.** While measuring simple species abundance is feasible, determining actual nursery productivity (such as survival and recruitment over time) is a long-term challenge. **Framework decision:** tiered metrics for Habitat and fisheries support, which utilize species community diversity (Shannon-Wiener index) alongside targeted juvenile densities (blue crab and fish abundance) to capture various facets of habitat function over time based on monitoring capacity.

Shellfish beds and oyster reefs

- **Site-Specific Reference Targets over Rigid Thresholds.** regional thresholds, such as the standard "passing grade" of 15 oysters/m² versus the target goal of 50 oysters/m² are limited in understanding performance. Experts emphasized that because natural systems naturally vary (with some struggling to reach 10/m² while others exceed 200/m²), target metrics should come from site- or tributary-specific numbers derived from long-term monitoring at local reference sites. **Framework decision:** include comparison of restored reef characteristics against localized reference conditions rather than prescribing rigid, uniform numbers.
- **Intertidal vs. Subtidal.** Primary objectives differ fundamentally between intertidal living shorelines (where wave attenuation, sediment accretion, and shoreline protection are the main goals) and subtidal reef sanctuaries (which focus on filtration, nutrient cycling, and fisheries support). **Framework decision:** where applicable, distinguish subtidal (S) and intertidal (I) indicators to avoid burdening site managers with irrelevant measurements.

- **Modernizing Functional Cycling Calculators.** Regulatory agencies rely on ecosystem service calculators (such as Grabowski models) that are decades old. Experts recommended including in-situ, direct functional measurements. **Framework decision:** include in-situ, direct functional metrics (e.g., sediment denitrification rate and sediment nutrient flux) instead of solely relying on static, generic lookup models.

Coastal saltmarshes and reedbeds

- **Vegetation Cover Baselines vs. Regulator Demands.** While Maryland regulators frequently mandate an arbitrary 85% planting cover threshold for living shoreline success, experts emphasized that natural, healthy marshes often exhibit lower coverage. Criteria should rely on comparisons with a local reference marsh sharing similar tidal and inundation parameters rather than rigid percentage rules. **Framework decision:** interpret vegetation cover metrics alongside reference site trajectories.
- **Hydrology and Soil Porewater as Leading Indicators.** Experts emphasized the importance of tidal hydrology (inundation range and duration) for overall marsh health and function. Soil porewater salinity was recognized as a vital leading indicator of long-term marsh resilience and functional health. **Framework decision:** include tidal and salinity regime (porewater salinity) under environmental conditions supporting marsh recovery and persistence.
- **Limitations of UVVR and the Need for Multi-Metric Approach to Assess Marsh Stability.** While the Unvegetated-to-Vegetated Marsh Ratio (UVVR) is valuable as a high-level scoping tool of above-ground biomass, experts cautioned that it is insufficient on its own. Belowground root-rhizome biomass was highlighted as a much better predictor of marsh stability, as degradation can occur underground long before a marsh visibly wanes. **Framework decision:** combine spatial indices (UVVR) with site-specific vegetation health (above and below-ground biomass) and sediment accretion measurements to assess overall marsh sustainability.
- **Feasibility, Scale, and Technology Barriers.** Measuring sediment dynamics and accretion (such as through surface elevation tables) is highly expensive and slow. Participants proposed utilizing periodic LiDAR drone surveys and remote sensing over broad spatial scales. **Framework decision:** This discussion shaped the modular structure of the framework, allowing local managers to select feasible, scale-appropriate metrics rather than requiring complete prescriptive monitoring protocols. Technological advances in monitoring can be integrated in future work.