Coastal Habitats
9. Seagrass Restoration

DEFINITION

Seagrasses are flowering plants that grow entirely underwater and form dense meadows in shallow areas (Reynolds 2018). *Seagrass restoration* refers to any activities that help return seagrass ecosystems to as close as possible to their state before anthropogenic disturbances (Paling et al. 2009). Seagrass restoration helps improve water quality, attenuates waves and is a source of blue carbon sequestration. A healthy seagrass ecosystem has positive spillover effects to adjacent coastal ecosystems such as coral reefs and beaches (Olander et al. 2021). Seagrass beds are widespread throughout the coastal waters of the United States. While the species of seagrass vary by region, US seagrasses span from the Alaskan coast to Caribbean Sea (Gumusay et al. 2019). Seagrass populations are declining as a result of coastal development, degraded water quality, and the impacts of climate change such as ocean acidification and rising ocean temperature (Waycott et al. 2009; UNEP 2023). Fortunately, steps can be taken to restore seagrass beds, including transplanting seagrass, seeding seagrass, and modifying sediment to induce seagrass growth (Olander et al. 2021).

TECHNICAL APPROACH

Many earlier seagrass restoration projects focused solely on reducing environmental stressors such as poor water quality and nutrient pollution (Valdez et al. 2020). Nutrient pollution can be reduced by restoring riparian buffers, limiting fertilizer runoff from agricultural areas, and containing waste runoff from animals. Other stressors that can be reduced are improved water clarity and sediment stability (Lefcheck et al. 2018). To improve water clarity, particulate matter and trash must be removed from the water. Since seagrass beds further away from human development generally have higher water clarity, managed retreat from the shoreline can serve as a restoration strategy (Saunders et al. 2013). Achieving greater sediment stability involves controlling populations of bioturbators, animals that disrupt the sediment. The most prominent bioturbator is the lugworm (*Arenicola marina*) (Suykerbuyk et al. 2016). There have been recent successes using active restoration, such as the following techniques:

- **Transplanting seagrass:** Transplanting seagrass involves moving plants from a donor site to the restoration site. It is important that the donor and recipient beds have similar environmental conditions, including water depth, water quality, salinity, and exposure to wave energy. When choosing individual plants to transport, plants that have minimal damage to their meristematic tissue (areas that can produce new growth) will be most likely to survive once planted at the restoration site (Short and Coles 2001). While seagrass transplantation can be performed by hand, machines have been shown to increase survivorship rates. Mechanical systems have been developed that can cut seagrass sods and then plant them at the restoration site (Paling et al.

2001). When planting seagrass beds, it is important to space plants to maximize positive species interactions. Planting seagrasses near each other, or positive density dependence, facilities reproduction and helps beds collectively weather environmental stressors (Valdez et al. 2020). However, in low-stress environments, it is important not to plant seagrasses too closely as the plants may shade each other and limit growth (Ralph et al. 2007).

- **Seeding seagrass:** As an alternative to transplantation, which can significantly degrade donor meadows, seagrass seedlings can be germinated in a nursery. Seagrass seedlings can be grown in large quantities in this way and subsequently planted at the restoration site (Tuya et al. 2017). Unfortunately, these seedlings have suffering high mortality rates due to difficulty of adjusting to an environment characterized by high wave energy, pathogens, and high sedimentation (Balestri and Lardicci 2012). To increase the chances of survival, artificial seagrass leaves can be placed around the plantings to protect them (Tuya et al. 2017).
- **Modifying sediment to encourage seagrass growth:** Light is a key factor limiting seagrass growth. Suspended sediment in the water attenuates light, limiting the amount that is available to the seagrass and thus reducing growth (Adams et al. 2016). To enhance seagrass growth, restoration projects have reduced the amount of suspended sediment to allow more light to penetrate deeper into the water. Studies have shown that adding coarse beach sand to the sediment at the restoration site helps reduce the amount of sediment suspended in the water (Jiang et al. 2022).

OPERATIONS AND MAINTENANCE

After seagrass restoration is completed, it is important to limit boat traffic near the site to prevent damage and disturbance to the seagrass plants. Invasive species and bioturbators frequently need to be removed to reduce seagrass mortality. Actions to reduce nutrient pollution reaching the restoration site, such as vegetating the shoreline to reduce runoff, are also helpful for the long-term sustainability of the restoration project.

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **High light availability:** Light is a primary limiting factor for seagrass growth. Seagrasses are photosynthetic plants that rely on light penetrating below the water's surface for survival. As light exposure increases, so does the likelihood of seagrass survival (Bertelli et al. 2022).
- ✓ **Little to no salinity fluctuations:** While seagrasses are adapted to the salty conditions of the ocean, rapid fluctuations in salinity can cause mass die-offs. The primary source of salinity imbalances are desalinization plants used to produce freshwater (Garrote-Moreno et al. 2014).
- ✓ **Depth between 0.8 and 1.5 m:** This range encompasses the general area where enough light penetrates to support seagrasses. While some species can grow deeper than this depending on light availability, high turbidity environments make this unlikely (Aoki et al. 2020).

- ✓ **History of previous seagrass growth:** Historic seagrass populations often serve as a proxy for ideal conditions for seagrass restoration (van Katwijk et al. 2009).
- ✓ **Higher bivalve (*Bivalvia* spp.) biomass:** Bivalves and seagrasses are mutualistic species. Seagrasses help stabilize sediments, which results in favorable conditions for bivalves. Meanwhile, bivalves help absorb sulfur, a threat to seagrasses. Existing bivalve populations help seagrasses get established (Gräfnings et al. 2023).
- ✗ **High wave energy:** Seagrasses grow in areas that are relatively sheltered and receive low to moderate wave energy. Seagrass seeds and transplants struggle to establish in high wave energy environments (van Katwijk et al. 2009).
- ✗ **High populations of ragworms (*Nereididae spp*.) and lugworms (*Arenicola marina*):** Both ragworms and lugworms are bioturbators that increase the amount of sediment suspended in the water. This limits light availability for the seagrasses, reducing their growth (Gräfnings et al. 2023; Suykerbuyk et al. 2016).
- ✗ **Near a significant source of nutrient pollution:** Nutrient pollution promotes the growth of algae, which limits the amount of light available to the seagrasses below.
- ✗ **High boat traffic:** Seagrasses suffer significant damage from boat propellers and boat groundings. It is recommended that recreational boaters be excluded from restoration sites (Paling et al. 2009).
- ✗ **Near dredged area or area where dredged sediment will be deposited:** Dredging causes large amounts of sediments to be suspended in the water, increasing turbidity and reducing light availability for the seagrasses. Furthermore, dredging deepens channels, making the area unsuitable for seagrass growth (Paling et al. 2009).

TOOLS, TRAINING, AND RESOURCES FOR PLANNING AND IMPLEMENTATION

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Guidelines for the Restoration and Conservation of Seagrasses in the United States and Adjacent Waters	Guidebook	1998	National Oceanic and Atmospheric Administration (NOAA)	National	This comprehensive guide covers every aspect of seagrass restoration from project planning to monitoring. The guide also gives a regional breakdown of permitting requirements needed for a project.	✓	✓	✓	—
Eelgrass Restoration on the US West Coast	Guidebook	2021	Pacific Marine and Estuary Fish Habitat Partnership	US West Coast	In a search to find the most effective restoration practices, the authors reviewed numerous restoration projects. Additionally, the guide includes case studies and recommendations to practitioners.	✓	✓	—	✓
Seagrass Restoration Handbook—UK & Ireland	Guidebook	2021	UK Environment Agency	Designed for the British Isles but most of the information is more broadly applicable	This guide gives helpful insights into seagrass restoration techniques, including transplanting beds and growing seeds in nurseries. There is also an in-depth explanation of best monitoring practices and indicators of seagrass health.	✓	✓	✓	—
Small-Scale SAV Restoration in Chesapeake Bay	Guidebook	2021	Chesapeake Bay Program's Submerged Aquatic Vegetation (SAV) Work Group	Designed for the Chesapeake Bay but most of the information is more broadly applicable	Covering the process of collecting and then replanting seagrass seeds and plants, this guide helps managers determine the ideal habitat criteria for their project. Additional topics covered include permitting, storing seeds and monitoring.	✓	✓	✓	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes			
						Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Seagrass Restoration	Book chapter	2009	Eric I. Paling, Mark Fonseca, Marieke M. van Katwijk, and Mike van Keulen	Global	The authors overview key issues pertaining to seagrass restoration as well as describing current restoration activities across the world. Additional topics covered include the costs of restoration and the valuation of ecosystem services.	—	—	—	✓
Seagrass Restoration Monitoring	Book chapter	2017	Committee on Effective Approaches for Monitoring and Assessing Gulf of Mexico Restoration Activities; The National Academies of Sciences, Engineering, and Medicine	Designed for the Gulf of Mexico but most of the information is more broadly applicable	Part of a larger book about ecological monitoring in the Gulf of Mexico, this chapter provides in-depth information about monitoring seagrass restoration projects. The authors discuss different monitoring metrics and planning considerations.	—	—	✓	—
Seagrasses: Biology, Ecology and Conservation	Guidebook	2007	Bronwyn M. Gillanders	Global	Covering all aspects of the seagrass ecosystem, the authors give insight into the ecological processes that drive a healthy seagrass ecosystem. Seagrass conservation biology is investigated as a way to better inform restoration projects.	✓	—	—	✓
SAVing the Gulf: Submerged Aquatic Vegetation	Guidebook	2015	Mobile Bay National Estuary Program	Designed for the Gulf of Mexico but most of the information is more broadly applicable	This guide outlines the different plants that make up the seagrass ecosystem. The guide also provides restoration techniques, monitoring advice, and suggestions for involving the local community.	✓	—	✓	—

GRAY INFRASTRUCTURE ALTERNATIVES

Seagrass restoration can be an alternative to several gray infrastructure approaches that reduce the effects of shoreline erosion and coastal flooding: bulkheads, riprap/revetments, seawalls, groins, and artificial breakwaters. The ability of a seagrass restoration project to replace or supplement one of these gray infrastructure types depends strongly on the project's location and whether it is designed to create the necessary outcomes. Certain environmental conditions may require gray infrastructure rather than seagrass restoration. See the gray infrastructure alternative tables in Section 1 for a comparison of seagrass restoration to these alternatives.

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Storm protection:** Seagrasses are highly effective at attenuating waves during severe storms. Seagrasses often have extensive root networks, preventing them from being uprooted by strong waves. Flexible and resilient seagrass leaves are well-suited to dissipate wave energy before it reaches the coast. By anchoring the seabed, seagrasses limit changes to the bathymetry caused by storms, keeping the coast intact (James et al. 2021).
- **Reduced flooding:** Seagrasses help retain sediments, which stabilizes the coastline. During storm surges, the coastal areas protected by seagrasses experience less erosion and inland water penetration. By restoring natural sediment processes, seagrasses allow for coastlines to be better prepared for flooding (James et al. 2019).
- **Sea level rise adaptation and resilience:** Working in tandem with coral reefs, seagrasses can reduce the impacts of sea level rise. While seagrasses cannot survive in high wave energy environments, they can alter tidal regimes, preventing water from reaching further inshore. When coral reefs are also present, they help shelter nearby seagrass from high wave energy, allowing the seagrass to better adapt to rising seas (Keyzer et al. 2020).
- **Carbon storage and sequestration:** Seagrass meadows capture and bury carbon at a higher rate per acre than tropical rainforests. Sediments in seagrass ecosystems can absorb carbon indefinitely, allowing carbon to be kept out of the atmosphere for thousands of years. However, degraded seagrasses can change from carbon sinks to sources of carbon emissions, highlighting the importance of restoration (Macreadie et al. 2014).

Social and Economic

- **Reduced erosion:** Seagrass beds are highly effective at reducing erosion because their dense mats of roots stabilize sediment and their leaves attenuate waves. Furthermore, seagrasses can trap sediment, causing accretion, which provides a supply of sediment to naturally nourish the shoreline (Christianen et al. 2013).

- **Mental health and well-being:** Healthy seagrass ecosystems enhance the overall health of the coast, increasing recreational opportunities and thus boosting mental health and psychological well-being.
- **Resilient fisheries:** Seagrasses host many fish species during at least some point of their life cycles, with many species using seagrass beds as nursery grounds. Many species that fish prey on also rely on seagrasses. Furthermore, seagrass meadows are a source of detritus that benefits fish that do not live in the seagrass (Gillanders 2007).
- **Cultural values:** Seagrass meadows are valuable ecosystems that are often not well-understood by the general public. Seagrass restoration can help raise awareness and cultural appreciation of this ecosystem (Cullen-Unsworth et al. 2014).
- **Jobs:** Workers will need to be hired to implement the restoration project, supporting the local economy.
- **Recreational opportunities:** Restored seagrass habitats can be popular venues for snorkeling, kayaking, and wildlife viewing. Charismatic species such as manatees and green sea turtles often reside in seagrasses. However, many small seagrass restoration projects cannot support such large fauna (Olander et al. 2021).
- **Public health and safety:** Many seagrass plants produce natural biocides that kill off bacterial pathogens such as *Vibrio* species. These pathogens are detrimental to both human and aquatic health, with many pathogens that target corals eliminated by seagrasses (Lamb et al. 2017). However, biocide production may not be uniform across different seagrass meadows, as this relationship has only been studied in certain areas (Olander et al. 2021).

Ecological

- **Enhanced biodiversity:** Seagrass restoration has been shown to increase biodiversity by 43% to 45% compared to degraded habitats. Seagrass habitats host a variety of species including bivalves, crustaceans, and fish. They also serve as vital nursery grounds for fish that spend the majority of their life cycles in other habitats. The biodiversity benefits of seagrasses are greatest in shallow waters (McHenry et al. 2021).
- **Improved water quality:** Seagrasses have been shown to absorb excess particulate matter, sediments, and nutrients in the water (Moore 2004, de los Santos et al. 2020). Seagrasses stabilize the ocean bed and create a sheltered environment from the rest of the ocean, allowing particles suspended in the water to become trapped. This reduces levels of turbidity in the surrounding water (Moore 2004). Photosynthesis performed by seagrasses infuses additional oxygen into the water, increasing dissolved oxygen rates. On coastlines increasingly plagued by eutrophication and low dissolved oxygen levels, seagrasses can help breathe life back into the whole ecosystem (Shoji and Tomiyama 2023).
- **Increased primary productivity:** Increases in seagrass biomass have resulted in increases in primary productivity in the ecosystem. As mentioned earlier, seagrasses can store carbon for thousands of years. As levels of carbon dioxide increase in the ocean, seagrass photosynthesis rises as well, further expanding the primary productivity of the ecosystem (Russell et al. 2013).

BARRIERS AND SOLUTIONS FOR PRACTITIONERS

Common Barriers

Several barriers are common across many of the nature-based solutions strategies; these are described in more detail in Section 1 of the Roadmap. Additional notes about the barriers specific to seagrass restoration are included here.

- **Expense:** Out of all the coastal ecosystems, seagrasses are among the most expensive to restore. The cost of seagrass restoration varies widely, with reported expenditures between $244,634 to $4,695,002 per acre in the United States (Paling et al. 2009). This means that most seagrass restorations are small in scale, with few restored seagrass beds large enough to host marine megafauna. However, due to economies of scale, larger projects tend to be cheaper per acre because the capital costs are distributed over a greater area (Bayraktarov et al. 2016).
- **Capacity**
- **Public opinion**
- **Conflict with other land uses:** Land reclamation, which involves dredging sediment to create new land in coastal areas, is a significant driver of seagrass decline. Seagrass meadows are often targeted for land reclamation because of their shallow depth and proximity to the coast. Land reclamation is expensive and only completed in urban areas, making it difficult to conserve seagrasses in these areas (Yaakub et al. 2014).
- **Regulation**
- **Lack of effectiveness data**

Economic

- **Frequent ship traffic:** Ship channels often need to be widened or deepened to accommodate larger commercial vessels as they enter nearby ports. Dredging these channels results in high levels of sedimentation and turbidity, significantly worsening conditions for seagrasses. Ports are the economic engines for many coastal communities, making it difficult to avoid the impacts on seagrass meadows (Erftemeijer and Robin Lewis 2006).

Community

- **Degradation from boating:** With increasing coastal development, recreational boating has become a significant problem for seagrass meadows. Boat wakes disturb invertebrate populations, limiting the effectiveness of seagrasses as nurseries and causing ripple effects up the food chain. Boat wakes also resuspend sediment, reducing the amount of light that reaches seagrasses and limiting their growth (Bishop 2008). Propeller scars from boats remove seagrasses from the sediment, reducing ecosystem health and resiliency (Bell et al. 2002).

- **Impacts of fishing:** Both recreational and commercial fishers have significantly degraded seagrass meadows. Chronic overfishing has significantly reduced fish populations in seagrasses, reshuffling the food web (Guiry et al. 2021). Furthermore, abandoning fish boats, gear, and crab traps significantly degrades seagrasses. Special restoration techniques are needed to restore an area fouled by rusting debris (FDEP 2023).

Ecological

- **Agriculture, aquaculture, and wastewater runoff:** Seagrasses are often located close to the coast, situating them closer to sources of nutrient pollution. Aquaculture discharge, agricultural runoff and wastewater effluent are the primary sources of nutrient pollution that reach seagrass meadows. The excess nutrients cause eutrophication, which limits the amount of light available to them, reducing growth and biodiversity (Orth et al. 2006).
- **Invasive species:** Invasive species are often transported via shipping or aquaculture to seagrass meadows. Introduced seaweeds, bioturbators, worms, algae, and mussels all have deleterious impacts on the seagrass ecosystem. Invasive species increase the herbivory load on the seagrass, reducing canopy cover. Bioturbators and algae block sunlight from reaching the seagrass, limiting photosynthesis and plant growth. Invasive mussels impede rhizome propagation, which reduces canopy cover (Williams 2007).
- **Slow seagrass recruitment:** Despite improvements in water quality and newly transplanted seagrass, seagrass recovery is often slow after restoration. This is usually due to the lack of genetic diversity within the degraded seagrass bed. Larger scale restoration projects often avoid this barrier because there are enough new individual plants to form a genetically diverse community. Additionally, new seed-based restoration techniques are more effective at providing greater genetic diversity (Stewart-Sinclair et al. 2020).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
San Francisco- Oakland Bay Bridge Eelgrass Restoration Project	San Francisco Bay, CA	NOAA, San Francisco State University	Paper-stick transplant method, seed buoys, bamboo stake transplant method	70	2.5 million	9 years	After an oil spill significantly degraded eelgrass beds in the San Francisco Bay, contractors worked to restore the beds. They pioneered techniques, including the use of buoys that dispersed seeds.	No	Sharp swings in temperature and salinity wiped out most of the pilot sites. However, the project went ahead and planted the seagrass in dense beds with ample space in between the beds. This promoted significant growth.
Drakes Estero Restoration Project	Point Reyes National Seashore, CA	**National Park Service (NPS),** Point Reyes National Seashore Association	Removing oyster racks and other debris	1	4,000,000	3 years	Drakes Estero was previously used for mariculture, which resulted in a significant amount of debris accumulating in the water. Divers removed the debris, which blocked light, and the eelgrass beds naturally grew back.	No	A custom-designed excavator bucket was used to remove debris without damaging the seagrass.
Miami Harbor Seagrass Restoration Project	Miami, FL	US Army Corps of Engineers (USACE)	Hand transplant method	17	N/A	5 years	To mitigate seagrass loss resulting from dredging in the Miami Harbor, 29,000 individual plants were transplanted to the restoration site. Bird roosting stakes were also installed to provide passive fertilization.	Severe storms, coastal flooding, sea level rise	While being transported on a boat, the seagrasses were bathed in ambient seawater.

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Burtons Bay Seagrass Restoration Project	Onley, VA	Virginia Department of Environmental Quality, Virginia Institute of Marine Sciences, The Nature Conservancy	Hand transplant method	60	2.25 million	Ongoing	Volunteer divers fill tanks with seeds and eelgrass cuttings. The plants are then taken to the restoration site.	Severe storms, coastal flooding, sea level rise	The project is participating in a blue carbon market to potentially fund future restoration efforts.
West Galveston Bay Seagrass Restoration Project	Galveston, TX	Galveston Bay Foundation, US Environmental Protection Agency, Texas Natural Resources Conservation Commission	Peat pot transplant method	2.5	1000,000	16 months	Seagrasses were placed in holding tanks and covered in wet burlap during transport in between the donor site and the restoration site. Transplants were then planted in peat pots at the restoration site.	Severe storms, coastal flooding, sea level rise	Shallower beds were far more successful than deeper beds, highlighting the importance of planting in shallow water.
Boston Harbor Eelgrass Restoration Project	Boston, MA	**NPS,** Massachusetts Division of Marine Fisheries, USACE	Combination of hand and polyvinyl chloride (PVC) pipe transplant methods	5	5000,000	4 years	Construction of a natural gas pipeline was set to destroy a seagrass bed in Boston Harbor. Workers removed the seagrasses to a similar site nearby before they were degraded.	Severe storms, coastal flooding, sea level rise	The PVC frames attracted macroalgae to the site and were subsequently removed.

Bolding indicates DOI affiliates.

REFERENCES

Adams, M. P., R. K. Hovey, M. R. Hipsey, L. C. Bruce, M. Ghisalberti, R. J. Lowe, R. K. Gruber, et al. 2016. “Feedback between Sediment and Light for Seagrass: Where Is It Important?” *Limnology and Oceanography* 61(6): 1937–55. https://doi.org/10.1002/lno.10319.

Aoki, L. R., K. J. McGlathery, P. L. Wiberg, and A. Al-Haj. 2020. “Depth Affects Seagrass Restoration Success and Resilience to Marine Heat Wave Disturbance.” *Estuaries and Coasts* 43: 316–28. https://doi.org/10.1007/s12237-019-00685-0.

Balestri, E., and C. Lardicci. 2012. “Nursery-Propagated Plants from Seed: A Novel Tool to Improve the Effectiveness and Sustainability of Seagrass Restoration.” *Journal of Applied Ecology* 49(6): 1426–35. https://doi.org/10.1111/j.1365-2664.2012.02197.x.

Bayraktarov, E., M. I. Saunders, S. Abdullah, M. Mills, J. Beher, H. P. Possingham, P. J. Mumby, and C. E. Lovelock. 2016. “The Cost and Feasibility of Marine Coastal Restoration.” *Ecological Applications* 26(4): 1055–74. https://doi.org/10.1890/15-1077.

Bell, S. S., M. O. Hall, S. Soffian, and K. Madley. 2002. “Assessing the Impact of Boat Propeller Scars on Fish and Shrimp Utilizing Seagrass Beds.” *Ecological Applications* 12(1): 206–17. https://doi.org/10.1890/1051-0761(2002)012[0206:ATIOBP]2.0.CO;2.

Bertelli, C. M., H. J. Stokes, J. C. Bull, and R. K. F. Unsworth. 2022. “The Use of Habitat Suitability Modelling for Seagrass: A Review.” *Frontiers in Marine Science* 9. https://www.frontiersin.org/articles/10.3389/fmars.2022.997831.

Bishop, M. J. 2008. “Displacement of Epifauna from Seagrass Blades by Boat Wake.” *Journal of Experimental Marine Biology and Ecology* 354(1): 111–18. https://doi.org/10.1016/j.jembe.2007.10.013.

Christianen, M. J. A., J. van Belzen, P. M. J. Herman, M. M. van Katwijk, L. P. M. Lamers, P. J. M. van Leent, and T. J. Bouma. 2013. “Low-Canopy Seagrass Beds Still Provide Important Coastal Protection Services.” *PLOS ONE* 8(5): e62413. https://doi.org/10.1371/journal.pone.0062413.

Cullen-Unsworth, L. C., L. M. Nordlund, J. Paddock, S. Baker, L. J. McKenzie, and R. K. F. Unsworth. 2014. “Seagrass Meadows Globally as a Coupled Social–Ecological System: Implications for Human Wellbeing.” *Marine Pollution Bulletin* 83(2): 387–97. https://doi.org/10.1016/j.marpolbul.2013.06.001.

de los Santos, C. B., I. Olivé, M. Moreira, A. Silva, C. Freitas, R. A. Luna, H. Quental-Ferreira, et al. 2020. “Seagrass Meadows Improve Inflowing Water Quality in Aquaculture Ponds.” *Aquaculture* 528: 735502. https://doi.org/10.1016/j.aquaculture.2020.735502.

Erftemeijer, P. L. A., and R. R. R. Lewis. 2006. “Environmental Impacts of Dredging on Seagrasses: A Review.” *Marine Pollution Bulletin* 52(12): 1553–72. https://doi.org/10.1016/j.marpolbul.2006.09.006.

FDEP. 2023. *Seagrass Restoration Efforts*. Tallahassee, FL: Florida Department of Environmental Protection. https://floridadep.gov/rcp/rcp/content/seagrass-restoration-efforts.

Garrote-Moreno, A., Y. Fernández-Torquemada, and J. L. Sánchez-Lizaso. 2014. "Salinity Fluctuation of the Brine Discharge Affects Growth and Survival of the Seagrass *Cymodocea nodosa*." *Marine Pollution Bulletin* 81(1): 61–8. https://doi.org/10.1016/j.marpolbul.2014.02.019.

Gillanders, B.M. 2007. "Seagrasses, Fish, and Fisheries." In *Seagrasses: Biology, Ecology, and Conservation,* 503–05. Dordrecht, The Netherlands: Springer. https://link.springer.com/content/pdf/10.1007%2F978-1-4020-2983-7.pdf.

Gräfnings, M. L. E., L. L. Govers, J. H. T. Heusinkveld, B. R. Silliman, Q. Smeele, S. R. Valdez, and T. van der Heide. 2023. "Macrozoobenthos as an Indicator of Habitat Suitability for Intertidal Seagrass." *Ecological Indicators* 147: 109948. https://doi.org/10.1016/j.ecolind.2023.109948.

Guannel, G., K. Arkema, P. Ruggiero, and G. Verutes. 2016. "The Power of Three: Coral Reefs, Seagrasses and Mangroves Protect Coastal Regions and Increase Their Resilience." *PLOS ONE* 11(7): e0158094. https://doi.org/10.1371/journal.pone.0158094.

Guiry, E. J., J. R. Kennedy, M. T. O'Connell, D. R. Gray, C. Grant, and P. Szpak. 2021. "Early Evidence for Historical Overfishing in the Gulf of Mexico." *Science Advances* 7(32): eabh2525. https://doi.org/10.1126/sciadv.abh2525.

Gumusay, M., T. Bakırman, I. T. Kizilkaya, and N. O. Aykut. 2019. "A Review of Seagrass Detection, Mapping and Monitoring Applications Using Acoustic Systems." *European Journal of Remote Sensing* 52(1): 1–29. https://doi.org/10.1080/22797254.2018.1544838.

James, R. K., A. Lynch, P. M. J. Herman, M. M. van Katwijk, B. I. van Tussenbroek, H. A. Dijkstra, R. M. van Westen, et al. 2021. "Tropical Biogeomorphic Seagrass Landscapes for Coastal Protection: Persistence and Wave Attenuation During Major Storms Events." *Ecosystems* 24: 301–18. https://doi.org/10.1007/s10021-020-00519-2.

James, R. K., R. Silva, B. I. van Tussenbroek, M. Escudero-Castillo, I. Mariño-Tapia, H. A. Dijkstra, R. M. van Westen, et al. 2019. "Maintaining Tropical Beaches with Seagrass and Algae: A Promising Alternative to Engineering Solutions." *BioScience* 69(2): 136–42. https://doi.org/10.1093/biosci/biy154.

Jiang, Z., S. Liu, L. Cui, J. He, Y. Fang, C. Premarathne, L. Li, Y. Wu, X. Huang, and M. Kumar. 2022. "Sand Supplementation Favors Tropical Seagrass *Thalassia hemprichii* in Eutrophic Bay: Implications for Seagrass Restoration and Management." *BMC Plant Biology* 22: 296. https://doi.org/10.1186/s12870-022-03647-0.

Keyzer, L. M., P. M. J. Herman, B. P. Smits, J. D. Pietrzak, R. K. James, A. S. Candy, R. E. M. Riva, et al. 2020. "The Potential of Coastal Ecosystems to Mitigate the Impact of Sea-Level Rise in Shallow Tropical Bays." *Estuarine, Coastal and Shelf Science* 246: 107050. https://doi.org/10.1016/j.ecss.2020.107050.

Lamb, J. B., J. A. J. M. van de Water, D. G. Bourne, C. Altier, M. Y. Hein, E. A. Fiorenza, N. Abu, J. Jompa, and C. D. Harvell. 2017. "Seagrass Ecosystems Reduce Exposure to Bacterial Pathogens of Humans, Fishes, and Invertebrates." *Science* 355(6326): 731–33. https://doi.org/10.1126/science.aal1956.

Lefcheck, J. S., R. J. Orth, W. C. Dennison, D. J. Wilcox, R. R. Murphy, J. Keisman, C. Gurbisz, et al. 2018. "Long-Term Nutrient Reductions Lead to the Unprecedented Recovery of a Temperate Coastal Region." *Proceedings of the National Academy of Sciences* 115(14): 3658–62. https://doi.org/10.1073/pnas.1715798115.

Macreadie, P. I., M. E. Baird, S. M. Trevathan-Tackett, A. W. D. Larkum, and P. J. Ralph. 2014. "Quantifying and Modelling the Carbon Sequestration Capacity of Seagrass Meadows – A Critical Assessment." *Marine Pollution Bulletin* 83(2): 430–39. https://doi.org/10.1016/j.marpolbul.2013.07.038.

McHenry, J., A. Rassweiler, G. Hernan, C. K. Uejio, S. Pau, A. K. Dubel, and S. E. Lester. 2021. "Modelling the Biodiversity Enhancement Value of Seagrass Beds." *Diversity and Distributions* 27(11): 2036–49. https://doi.org/10.1111/ddi.13379.

Moore, K. A. 2004. "Influence of Seagrasses on Water Quality in Shallow Regions of the Lower Chesapeake Bay." *Journal of Coastal Research* 10045: 162–78. https://doi.org/10.2112/SI45-162.1.

NOAA. 2015. *Natural and Structural Measures for Shoreline Stabilization*. Washington, DC: National Oceanic and Atmospheric Administration. https://coast.noaa.gov/data/digitalcoast/pdf/living-shoreline.pdf.

Olander, L., C. Shepard, H. Tallis, D. Yoskowitz, K. Coffey, C. Hale, R. Karasik, S. Mason, K. Warnell, and K. Wowk. 2021. *Gulf of Mexico Ecosystem Service Logic Models and Socioeconomic Indicators (GEMS): Seagrass Restoration*. Durham, NC: Duke University Nicholas Institute for Energy, Environment and Sustainability. https://nicholasinstitute.duke.edu/eslm/seagrass-restoration.

Orth, R. J., T. J. B. Carruthers, W. C. Dennison, C. M. Duarte, J. W. Fourqurean, K. L. Heck, A. R. Hughes, et al. 2006. "A Global Crisis for Seagrass Ecosystems." *BioScience* 56(12): 987–96. https://doi.org/10.1641/0006-3568(2006)56[987:AGCFSE]2.0.CO;2.

Paling, E. I., M. van Keulen, K. D. Wheeler, J. Phillips, R. Dyhrberg, and D. A. Lord. 2001. "Improving Mechanical Seagrass Transplantation." *Ecological Engineering* 18(1): 107–13. https://doi.org/10.1016/S0925-8574(01)00065-9.

Paling, M. F., M. Katwijk, and M. van Keulen. 2009. "Seagrass Restoration." In *Coastal Wetlands: An Integrated Ecosystems Approach*, edited by G. Perillo, E. Wolanski, D. R. Cahoon, and C. S. Hopkinson, 687–713. Cambridge, MA: Elsevier. https://pubs.usgs.gov/publication/5200354.

Ralph, P. J., M. J. Durako, S. Enríquez, C. J. Collier, and M. A. Doblin. 2007. "Impact of Light Limitation on Seagrasses." *Journal of Experimental Marine Biology and Ecology 350*(1): 176–93. https://doi.org/10.1016/j.jembe.2007.06.017.

Reynolds, P L.. 2018. "Seagrass and Seagrass Beds." Smithsonian Institution: Ocean Find Your Blue. https://ocean.si.edu/ocean-life/plants-algae/seagrass-and-seagrass-beds.

Russell, B. D., S. D. Connell, S. Uthicke, N. Muehllehner, K. E. Fabricius, and J. M. Hall-Spencer. 2013. "Future Seagrass Beds: Can Increased Productivity Lead to Increased Carbon Storage?" *Marine Pollution Bulletin* 73(2): 463–69. https://doi.org/10.1016/j.marpolbul.2013.01.031.

Saunders, M. I., J. Leon, S. R. Phinn, D. P. Callaghan, K. R. O'Brien, C. M. Roelfsema, C. E. Lovelock, M. B. Lyons, and P. J. Mumby. 2013. "Coastal Retreat and Improved Water Quality Mitigate Losses of Seagrass from Sea Level Rise." *Global Change Biology* 19(8): 2569–83. https://doi.org/10.1111/gcb.12218.

Shoji, J., and T. Tomiyama. 2023. “Influence of Vegetation Coverage on Dissolved Oxygen Concentration in Seagrass Bed in the Seto Inland Sea: Possible Effects on Fish Nursery Function.” *Estuaries and Coasts* 46: 1098–1109. https://doi.org/10.1007/s12237-023-01205-x.

Short, F. T., and R. G. Coles. 2001. *Global Seagrass Research Methods*. Amsterdam, The Netherlands: Elsevier. https://www.sciencedirect.com/book/9780444508911/global-seagrass-research-methods.

Sutton-Grier, A. E., K. Wowk, and H. Bamford. 2015. “Future of Our Coasts: The Potential for Natural and Hybrid Infrastructure to Enhance the Resilience of Our Coastal Communities, Economies and Ecosystems.” *Environmental Science & Policy* 51: 137–48. https://doi.org/10.1016/j.envsci.2015.04.006.

Stewart-Sinclair, P. J., J. Purandare, E. Bayraktarov, N. Waltham, S. Reeves, J. Statton, E. A. Sinclair, B. M. Brown, Z. I. Shribman, and C. E. Lovelock. 2020. “Blue Restoration – Building Confidence and Overcoming Barriers.” *Frontiers in Marine Science* 7. https://www.frontiersin.org/articles/10.3389/fmars.2020.541700.

Suykerbuyk, W., L. L. Govers, T. J. Bouma, W. B. J. T. Giesen, D. J. de Jong, R. van de Voort, K. Giesen, P. T. Giesen, and M. M. van Katwijk. 2016. “Unpredictability in Seagrass Restoration: Analysing the Role of Positive Feedback and Environmental Stress on *Zostera noltii* Transplants.” *Journal of Applied Ecology* 53(3): 774–84. https://doi.org/10.1111/1365-2664.12614.

Tuya, F., F. Vila, O. Bergasa, M. Zarranz, F. Espino, and R. R. Robaina. 2017. “Artificial Seagrass Leaves Shield Transplanted Seagrass Seedlings and Increase Their Survivorship.” *Aquatic Botany* 136: 31–34. https://doi.org/10.1016/j.aquabot.2016.09.001.

UNEP. 2023. “Five Ways Often-Unheralded Seagrasses Boost Biodiversity.” *United Nations Environment Programme*, March 1, 2023. https://www.unep.org/news-and-stories/story/five-ways-often-unheralded-seagrasses-boost-biodiversity.

Valdez, S. R., Y. S. Zhang, T. van der Heide, M. A. Vanderklift, F. Tarquinio, R. J. Orth, and B. R. Silliman. 2020. “Positive Ecological Interactions and the Success of Seagrass Restoration.” *Frontiers in Marine Science* 7. https://www.frontiersin.org/articles/10.3389/fmars.2020.00091.

van Katwijk, M. M., A. R. Bos, V. N. de Jonge, L. S. A. M. Hanssen, D. C. R. Hermus, and D. J. de Jong. 2009. “Guidelines for Seagrass Restoration: Importance of Habitat Selection and Donor Population, Spreading of Risks, and Ecosystem Engineering Effects.” *Marine Pollution Bulletin* 58(2): 179–88. https://doi.org/10.1016/j.marpolbul.2008.09.028.

Waycott, M., C. M. Duarte, T. J. B. Carruthers, R. J. Orth, W. C. Dennison, S. Olyarnik, A. Calladine, et al. 2009. “Accelerating Loss of Seagrasses across the Globe Threatens Coastal Ecosystems.” *Proceedings of the National Academy of Sciences* 106(30): 12377–81. https://doi.org/10.1073/pnas.0905620106.

Williams, S. L. 2007. “Introduced Species in Seagrass Ecosystems: Status and Concerns.” *Journal of Experimental Marine Biology and Ecology* 350(1): 89–110. https://doi.org/10.1016/j.jembe.2007.05.032.

Yaakub, S. M., L. J. McKenzie, P. L. A. Erftemeijer, T. Bouma, and P. A. Todd. 2014. “Courage under Fire: Seagrass Persistence Adjacent to a Highly Urbanised City–State.” *Marine Pollution Bulletin* 83(2): 417–24. https://doi.org/10.1016/j.marpolbul.2014.01.012.

Authors and Affiliations

Katie Warnell, Nicholas Institute for Energy, Environment & Sustainability, Duke University **Sara Mason,** Nicholas Institute for Energy, Environment & Sustainability, Duke University
Aaron Siegle, Duke University
Melissa Merritt, Nicholas School of the Environment, Duke University
Lydia Olander, Nicholas Institute for Energy, Environment & Sustainability, Duke University

Contributors

Tamara Wilson, US Department of the Interior
Whitney Boone, US Department of the Interior

Acknowledgments

The Department of the Interior's Nature-Based Solutions Working Group provided input and feedback on the DOI Nature-Based Solutions Roadmap throughout its development. This work was supported by the US Geological Survey National Climate Adaptation Science Center.

Citation

Warnell, K., S. Mason, A. Siegle, M. Merritt, and L. Olander. 2023. *Department of the Interior Nature-Based Solutions Roadmap*. NI R 23-06. Durham, NC: Nicholas Institute for Energy, Environment & Sustainability, Duke University. https://nicholasinstitute.duke.edu/publications/department-interior-nature-based-solutions-roadmap.

Nicholas Institute for Energy, Environment & Sustainability

The Nicholas Institute for Energy, Environment & Sustainability at Duke University accelerates solutions to critical energy and environmental challenges, advancing a more just, resilient, and sustainable world. The Nicholas Institute conducts and supports actionable research and undertakes sustained engagement with policymakers, businesses, and communities—in addition to delivering transformative educational experiences to empower future leaders. The Nicholas Institute's work is aligned with the Duke Climate Commitment, which unites the university's education, research, operations, and external engagement missions to address the climate crisis.

United States Department of the Interior

The US Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated Island Communities. The Department of the Interior plays a central role in how the United States stewards its public lands, increases environmental protections, pursues environmental justice, and honors our nation-to-nation relationship with Tribes.