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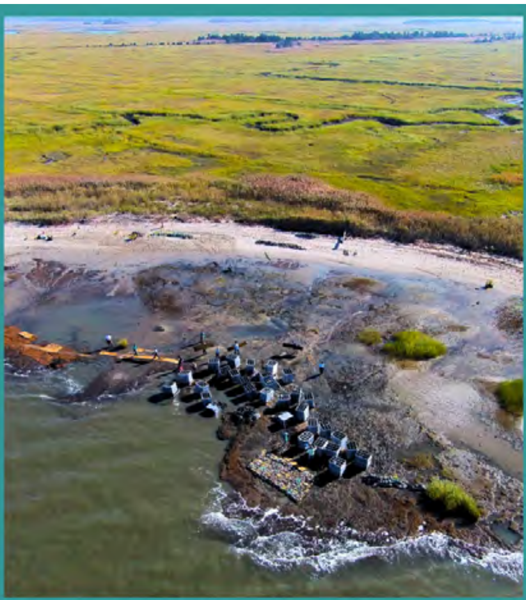




Department of the Interior Nature-Based Solutions Roadmap

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CONTENTS

Introduction

Nature-based solutions (NBS) are actions that incorporate natural features and processes to protect, conserve, restore, sustainably use, and manage natural or modified ecosystems to address socioenvironmental challenges while providing measurable cobenefits to both people and nature. They have great potential to enhance human well-being, improve ecosystem health, and support positive social and economic outcomes. Nature-based solutions are increasingly used to reduce climate risks including coastal and inland flooding, drought, wildfire, and urban heat. While many NBS strategies, such as reforestation and wetland creation, have been in use for a long time, recognition of these projects and opportunities for new applications are accelerating. Funding opportunities for such projects are also increasing and diversifying to include risk management and climate mitigation and adaptation.

Box 1. Is My Project a Nature-Based Solution?

- ✓ An action to protect, sustainably manage, or restore a natural or modified ecosystem
- ✓ Addresses a socioeconomic challenge (e.g., drought, flooding, wildfire)
- ✓ Expected to benefit nature
- ✓ Expected to benefit people or communities

The purpose of the Department of the Interior Nature Based Solutions Roadmap is to provide Department of the Interior (DOI) staff with consistent and credible information about nature-based solutions, such as which strategies match certain conditions and goals, what cobenefits they are likely to provide, example projects, and additional resources for project planning, construction, and monitoring. While this content was developed for a DOI audience, the information is likely applicable to any agency or practitioner engaged in planning or implementing an NBS project.

DOI manages more than 480 million acres of land in the United States, 55 million acres of tribal lands, more than 640 million acres of marine national monuments, and the 2.5-billion-acre Outer Continental Shelf through its bureaus and offices (DeSantis 2021). Given federal commitments to conserve lands and waters to benefit both people and nature and accelerate nature-based solutions nationally, viewing projects through this lens presents an opportunity for DOI to ensure its management approaches provide the greatest value to people while also improving ecosystem health. While many DOI projects fall under the umbrella of nature-based solutions, a strategic approach to project design, implementation, and adaptive management is likely to expand the benefits these projects provide to both people and ecosystems. Additional forthcoming guidance from DOI and individual bureaus and offices will provide more detail on authorization and direction for use of nature-based solutions within DOI. This is a living document and is not intended to be exhaustive of all NBS options available for implementation within the department. Future iterations will include updated NBS strategy information, as it becomes available, and new NBS strategies addressed over time.

An *NBS strategy* is defined as a certain type of NBS project. For example, living shorelines, urban greening, and prescribed fire are all strategies included in the Roadmap that can include various specific management or design approaches. The Roadmap has two main sections. Section 1 addresses cross-cutting NBS implementation principles and considerations relevant to all NBS strategies and approaches. Section 2 includes strategy-specific content with details on individual nature-based solutions along with further resources and information. For a full list of strategies, see the Section 2 Table of Contents. This Roadmap will be incorporated into an online NBS navigation tool for DOI at a later date. The information in the Roadmap has also been used to develop a series of fact sheets organized by NBS strategy.

Collectively, the information in the Roadmap is intended to introduce readers to the key concepts needed for planning and implementing nature-based solutions, help them identify particular NBS strategies applicable to their work context and aligned with their goals, and find relevant NBS resources, including design and construction guidance, planning tools, and example projects.

Section 1
Cross-Cutting Principles and Considerations

While NBS projects require site- and strategy-specific planning and design, the following principles and considerations are relevant across all NBS strategies and approaches and should be incorporated into every NBS project.

- **Engaging communities and including Indigenous Knowledges** in agency decision-making help to ensure projects meet the needs of tribal nations and communities, benefit from local experience, are equitably distributed, and contribute positively to public opinion and awareness of nature-based solutions.
- **Incorporating equity and environmental justice** principles into NBS design and implementation to ensure equitable project distribution both geographically and in terms of the both the potential benefits to people and nature and avoided negative impacts.
- **Identifying funding mechanisms and partnering opportunities** is critical for acquiring and leveraging support and expertise to make projects successful.
- **Understanding common barriers and regulatory processes** applicable to nature-based solutions can help planners identify and navigate potential obstacles.
- **Understanding NBS projects' costs and operation and maintenance needs**, and how those **compare to gray infrastructure approaches** with similar primary objectives, can help make the case for selecting nature-based solutions as alternatives to traditional infrastructure approaches.
- **Designing projects with adaptive management principles** addresses uncertainties in project design and allows for adjustment to optimize project outcomes over time.
- Communicating during project design and implementation about **cross-cutting benefits** that all NBS strategies can contribute to can maintain support and broaden awareness.

COMMUNITY ENGAGEMENT AND CONSULTATION

Nature-based solutions, by definition, are intended to benefit people and communities as well as natural ecosystems. Community and tribal engagement and consultation are critical in the planning and implementation of nature-based solutions to ensure that projects meet community and tribal needs, create outcomes that are equitably distributed, and are supported and sustained over time. Community engagement is also an important part of complying with government guidance and regulations. Office of Management and Budget Circular A-11 section 280 on Managing Customer Experience and Improving Service Delivery guides agencies to solicit feedback from communities that receive government services,

Box 2. Examples of Successful Community Engagement

Kiawah Island Natural Habitat Conservancy began its development of a nature-based solutions manual for the South Carolina island by speaking with key stakeholders. Their goals, concerns, and considerations for implementing nature-based solutions in their community informed the manual's content. A variety of factors informed the selection of nature-based solutions strategies to incorporate in the manual, including aesthetics, as tourism is a significant local industry; maintenance, to ensure projects are easy to sustain; and functionality, including the importance of monitoring project performance.

The Pocomoke River Restoration Partnership, which has restored over 3,000 acres of floodplain along the Pocomoke River in Maryland in the past decade, also depends on effective community engagement. Because much of the land in the floodplain is in private ownership, landowner participation is critical to the project's success. To streamline the process and avoid overwhelming landowners with information from the multiple partners involved this project, The Nature Conservancy led the process of engaging with interested property owners. They discussed options for land restoration, such as participation in federal programs, conservation easements, and direct collaboration with The Nature Conservancy. Ultimately, 24 landowners joined the project, resulting in the restoration of 75% of the floodplain in the project area.

which would include delivery of NBS projects. Additionally, most NBS projects executed by DOI are subject to National Environmental Policy Act (NEPA) requirements, which mandate meaningful opportunities for public participation. Community engagement can build on inclusion of local or Indigenous Knowledges that may inform the design of the NBS approach. A recent assessment of community engagement in 58 NBS projects across 21 cities found that enhanced engagement was associated with stronger and more diverse social outcomes, including sense of belonging, increased knowledge, and motivation for environmental stewardship (Kiss et al. 2022). Intentional community engagement has played a vital role in the success of many NBS projects (Box 2).

Effective community engagement and consultation requires careful planning, communication, and adaptability. A guidebook to community engagement for nature-based solutions (Sefton et al. 2023) and a study on assumptions that interfere with effective community engagement (Cross and Chappell 2022) provide best practices and strategies for avoiding common pitfalls of community engagement, summarized as follows:

- Before beginning community engagement, consider the purpose of the engagement from the project perspective and what benefits and risks participation might create for community members.

- Transparency is key, so clearly communicate what aspects of the project are open to community input and what decisions have already been made.
- Collaboration with local groups that have long-term ties to the community, especially if the project organization has limited community interaction, can be valuable. This can also clarify the local regulatory and permitting landscape to be navigated.
- To facilitate inclusive participation, provide the support needed for all interested community members. For example, one might create materials in different formats and languages, hold meetings on various days and times to accommodate work schedules, offer childcare, and compensate participants for their time.
- When discussing the project with participants, avoid assuming that the project will only create benefits for the community. Acknowledging the potential for negative outcomes can build trust and enable strategic planning to minimize those impacts.
- Finally, it is important to recognize that the goals and interests of individual community members may be different than the goals of the project team, and that different stakeholders may have conflicting goals.

DOI offices and bureaus already engage with communities in many ways, and the following DOI-specific resources can guide outreach or provide more intensive training:

- The online, interagency course Managing by Network, run by the Partnership and Community Collaboration Academy, focuses on partnership and community collaboration competencies, including building consensus with stakeholders, facilitating meetings, responding to conflict, mitigating risks, and assessing partnership performance.
- The National Park Service Stewardship Institute publishes case studies and reports related to community outreach, civic engagement, communication, and collaboration.
- The Bureau of Land Management's (BLM) Collaborative Action and Dispute Resolution program provides tools for BLM and stakeholders to prevent, manage, or resolve conflict and improve collaborative decision-making and land-use planning.
- BLM's Engaging with Communities in Public Land Stewardship toolkit provides guidance, tools, and best practices for partnering with local "friends groups," community-based organizations led by local volunteers.
- The US Fish and Wildlife Service's (USFWS) Stakeholder Engagement Wayfinder lays out an interactive framework for managers to engage with stakeholders, including techniques, case studies, and additional resources.
- An assessment of best practices for the USFWS to create and sustain engagement with urban communities was published in 2016.
- DOI's tribal consultation webpage includes up-to-date resources on DOI policies and procedures related to tribal consultation, including information on past and upcoming consultations.

INDIGENOUS KNOWLEDGES

In 2022, DOI Secretary Deb Haaland—a member of the Pueblo of Laguna—said, "from wildfire prevention to managing drought and famine, our ancestors have used nature-based approaches to coexist among our lands, waters, wildlife and their habitats for millennia. As communities continue to face the effects of climate change, Indigenous Knowledges will benefit the department's efforts to bolster resilience and protect all communities" (DOI 2022). This statement stresses DOI's commitment to the importance of incorporating Indigenous Knowledges into federal processes, especially when it comes to nature-based solutions. The 2022 White House Guidance also directs agencies to better understand Indigenous Knowledges, grow and maintain relationships with tribal nations and Indigenous peoples, and consider, include, and apply Indigenous Knowledges to federal research, policies, and decision-making (Prabhakar and Mallory 2022).

Indigenous Knowledges[1] are defined in the 2022 Guidance for Federal Agencies as "a body of observations, oral and written knowledge, innovations, practices, and beliefs developed by Tribes and Indigenous Peoples through interaction and experience with the environment." This collective body of knowledge "can be developed over millennia, continues to develop, and includes understanding based on evidence acquired through direct contact with the environment and long-term experiences, as well as extensive observations, lessons, and skills passed from generation to generation" (Prabhakar and Mallory 2022). Indigenous Knowledges are heterogenous, unique, and context-dependent (Prabhakar and Mallory 2022, Reed et al. 2022). Tribes and Indigenous peoples have been working with nature to help solve problems since time immemorial (Reed et al. 2022). However, in many Indigenous and tribal contexts, there is a slight disconnect between commonly cited definitions of nature-based solutions that conceptualize using nature or natural solutions to solve human problems, as opposed to thinking of humans as a part of nature and leveraging that reciprocal relationship (Reed et al. 2022; Reed 2022). Despite, and perhaps because of, these differences in conceptualizations of nature-based solutions, there is a wealth of information that federal agencies can gain from Indigenous Knowledges. White House guidance on Indigenous Knowledges issued in 2022 states the importance of "understanding that multiple lines of evidence or ways of knowing can lead to better-informed decision-making." Research has shown that actively involving Indigenous peoples and local communities is a key element of success for restoration projects, which encompass a significant number of the NBS strategies contained in this Roadmap (Reyes-García et al. 2019).

Agencies often lack the expertise to appropriately consider and apply Indigenous Knowledges (Prabhakar and Mallory 2022), but there are a growing number of resources that can guide their application and consideration in NBS planning and implementation. Many of these resources are described and linked in the White House Guidance on Indigenous Knowledge (Prabhakar and Mallory 2022) and the forthcoming DOI Indigenous Knowledges Policy and Indigenous Knowledges Handbook. The White House memorandum includes resources on topics such as planning ahead to incorporate Indigenous Knowledges, how to engage youth and elders, how to include Indigenous Knowledges in federal decision-making, considering

[1] Recent White House guidance uses the term *Indigenous knowledge* but recognizes a variety of related terms including *traditional ecological knowledge*, *traditional knowledge*, *Indigenous traditional knowledge*, and *native science*. DOI policy recommends the term *Indigenous Knowledges* to recognize that there are many different knowledges, rather than one unified knowledge.

Box 3. Examples of DOI Projects Including Indigenous Knowledges

- **Shared governance and research on sweetgrass in Acadia National Park:** The National Park Service (NPS) is working with citizens of Wabanaki Tribes—the Aroostook Band of Mi'kmaq, the Houlton Band of Maliseet (Wolastogiyik), the Passamaquoddy (Peskotomuhkati) Tribe at Sipayik, the Passamaquoddy Tribe at Indian Township, and the Penobscot Nation—to research how to use historic sweetgrass harvesting practices to enhance sweetgrass abundance (Prabhakar and Mallory 2022, Schmitt 2021).
- **Using traditional burning to adapt to climate change:** The US Geological Survey (USGS) is working with Indigenous peoples in California to apply cultural burning practices to make landscapes more resilient to climate change (Prabhakar and Mallory 2022, Climate Adaptation Science Centers 2020, Sommer 2020). Additionally, there are broader efforts to enhance federal/tribal partnerships for wildland fire research and management (Lake 2021).
- **Floodplain reconnection to restore tribal fisheries:** USFWS is working with the Confederated Tribes of the Siletz Indians to reconnect two miles of creek in Oregon to provide access to rearing and foraging habitats for culturally important fish and shellfish (USFWS n.d.).
- **Working with tribes to inform riparian restoration:** USGS scientists are conducting research with the San Carlos Apache Tribe to develop a restoration plan for culturally important riparian areas that are at risk from climate change (USGS 2020).

shared management structures, recognizing Indigenous methodologies, honoring Indigenous languages, applying Indigenous voice and style, citing Indigenous Knowledges, and building capacity and providing direct funding to tribes and Indigenous organizations. DOI has applied Indigenous Knowledges to specific NBS projects, and much can be learned from those past experiences (Box 3).

Historically, Indigenous Knowledges have been marginalized and excluded from federal research and policy decisions, with some exceptions (e.g., Kendall et al. 2017). To change this and meaningfully incorporate Indigenous Knowledges into NBS research and strategy implementation requires growing and maintaining relationships with tribal and Indigenous groups, coproducing knowledge, and considering comanagement and costewardship of implemented projects (Prabhakar and Mallory 2022). It is important to emphasize that relationships between federal entities and tribal and Indigenous groups must not be extractive; these relationships need to be mutually beneficial and built on trust and respect (Prabhakar and Mallory 2022).

Additional information on applying Indigenous Knowledges to nature-based solutions can be learned from recorded sessions of the USGS webinar series *Incorporating Indigenous Knowledges into Federal Research and Management*.

EQUITY AND ENVIRONMENTAL JUSTICE

Nature-based solutions can be used to increase equity and environmental justice. While one of the defining features of nature-based solutions is that they deliver benefits to people, NBS project developers need to consider who is receiving those benefits and whether they are being delivered in an equitable way. The 2022 White House NBS Roadmap (White House Council on Environmental Quality, White House Office of Science and Technology Policy, White House Domestic Climate Policy Office 2022) identifies interweaving equity as one of the guiding principles for NBS implementation. This means that consideration of equity and environmental justice should be standard practice during the planning, implementation, and monitoring stages of NBS projects, as well as ensuring that all forms of equity are considered for each project, including recognitional, procedural, distributional, and contextual equity.[2] The DOI Environmental Justice Strategic Plan is aligned with this priority, and outlines a vision "to provide outstanding management of the natural and cultural resources entrusted to us in a manner that is sustainable, equitable, accessible, and inclusive of all populations" (DOI 2016). DOI policy requires bureaus and offices ensure meaningful involvement of low-income, minority, and tribal populations in department programs, policies, and activities through proper public participation, existing grant programs, training, technical assistance, and educational opportunities (DOI 2017). Focusing NBS efforts on disadvantaged communities can help correct past environmental injustices by providing access to nature's benefits in communities that most need them.

FUNDING MECHANISMS AND PARTNERING OPPORTUNITIES

Partnering

Implementing NBS projects requires numerous types of expertise and input from many different perspectives and sources of knowledge (see the Community Engagement and Indigenous Knowledges sections). Because of the diversity of expertise required and the varied stakeholders invested, these projects often benefit from and are only possible through partnerships. Partnerships may form between federal, state, and local government entities; nonprofits; tribes; community organizations; the private sector; philanthropic organizations; academia; and other institutions. Partnerships can also bring together often-needed diverse expertise—for example, ecologists, natural resource managers, engineers, planners, and others.

2 *Recognitional equity* is accounting for knowledge and values of all stakeholders, *procedural equity* is inclusiveness in decision-making processes, *distributional equity* is equitable distribution of costs and benefits, *contextual equity* is the conditions that influence stakeholders' abilities to participate, gain recognition, and access benefits (McDermott et al. 2013).

Departmental and Supplemental Federal Funding Opportunities

There are numerous federal funding sources that can support nature-based solutions. Table A.1 is a sample of these available federal funding sources and is not meant to be comprehensive. Not every funding source will be applicable for every type of NBS project; however, these programs are a good place to begin when looking for project funding. While the majority of the programs listed in Table A.1 are not DOI funding sources, DOI project teams and/or their partners could apply for these funds to support NBS projects.

Table A.1 Departmental and supplemental federal funding programs that support NBS projects

Federal Funding Programs	Types of NBS Projects Supported
DOI US Bureau of Reclamation (USBR) WaterSMART Cooperative Watershed Management Program	Funding to help groups to develop a new or sustain an existing watershed group, complete watershed restoration planning activities, carry out watershed data collection efforts, and design watershed management projects
DOI USBR WaterSMART Environmental Water Resource Projects	Funding for water resources management projects that have an ecological benefit and nexus, including water conservation projects with a dedicated instream or ecological benefit, ecosystem restoration, and other watershed health projects
DOI Bureau of Indian Affairs Annual Tribal Climate Resilience Awards	Tribal NBS projects eligible for planning and implementation awards
DOI USBR WaterSMART Aquatic Ecosystem Restoration Program	Funding for large-scale aquatic ecosystem restoration projects that are collaboratively developed, have widespread regional benefits, and result in the improvement of the health of fisheries, wildlife, and aquatic habitat, including through the removal or modification of barriers to fish passage
DOI National Park Service Land and Water Conservation Fund State-side Funding	Conservation of important habitats that also provide public outdoor recreation access
DOI Office of Insular Affairs Coral Reef and Natural Resources Initiative	The Coral Reef and Natural Resources Initiative provides grant funding for management and protection of coral reefs and to combat invasive species in the insular areas, contributing to the health of coral reef ecosystems and other natural resources for long-term economic and social benefit
DOI USFWS Coastal Program	Conservation and restoration to enhance wildlife habitat and build coastal ecosystem resilience
DOI USFWS National Wildlife Refuge System Resiliency	Conservation and NBS projects to promote coastal resilience and climate adaptation, address invasive species threats, and provide for additional data collection needed to support successful natural resource resilience
Federal Emergency Management Agency (FEMA) Flood Mitigation Assistance Grant Program	NBS projects that contribute to flood prevention and disaster mitigation
FEMA Building Resilient Infrastructure and Communities	NBS projects that contribute to hazard mitigation
FEMA Pre-Disaster Mitigation Grant Program	NBS projects that contribute to flood prevention and disaster mitigation

Table A.1 Departmental and supplemental federal funding programs that support NBS projects *(continued)*

Federal Funding Programs	Types of NBS Projects Supported
National Fish and Wildlife Foundation (NFWF) America The Beautiful Challenge	Conservation and restoration projects to enhance watershed restoration, resilience, equitable access to nature, workforce development, and habitat connectivity
NFWF National Coastal Resilience Fund	NBS to protect coastal communities and enhance fish and wildlife habitats
National Oceanic and Atmospheric Administration (NOAA) Community-Based Restoration Program	Restoration of coastal habitats that provide ecosystem and human benefits
US Department of Agriculture (USDA) Urban and Community Forestry Program	Conservation, restoration, and enhancement of urban forests
USDA Agricultural Conservation Easement Program	Support for landowners, land trusts, and other entities to protect, restore, and enhance wetlands or working lands
USDA Healthy Forests Reserve Program	Support for landowners to restore, enhance, and protect forestland resources on private and tribal lands.
USDA Landscape Conservation Initiatives	Support for agricultural producers who implement environmentally beneficial actions
USDA Natural Resource Conservation Service (Watershed and Flood Prevention Operations Program; Watershed Rehabilitation Program; Regional Conservation Partnership Program)	Applications of NBS on working lands to provide flood reduction, water quality benefits, and biodiversity benefits
USDA Working Lands for Wildlife	Technical and financial assistance to participants who voluntarily make improvements to their working lands to support wildlife
US Department of Defense Readiness and Environmental Protection Integration (REPI) Program	Conservation and restoration projects that support military missions and communities surrounding military installations, especially those that enhance resilience to climate change
US Department of Housing and Urban Development Community Development Block Grant Program	NBS projects in urban areas that contribute to flood prevention
US Department of Transportation PROTECT Formula Program	NBS that provide protection to transportation infrastructure from climate threats
US Environmental Protection Agency (EPA) Building Blocks for Sustainable Communities	Green infrastructure projects in urban areas that help reduce flooding and provide water quality benefits
EPA Clean Water Act Nonpoint Source Grant	NBS projects that help reduce pollution
EPA Clean Water State Revolving Fund	NBS projects that provide water quality benefits
EPA Great Lakes Restoration Initiative	NBS projects that provide ecological and social benefits in the Great Lakes region

Table A.1 Departmental and supplemental federal funding programs that support NBS projects *(continued)*

Federal Funding Programs	Types of NBS Projects Supported
EPA Greening America's Communities Program	Green infrastructure projects in urban areas that help reduce flooding
EPA Superfund Redevelopment Program	NBS projects that support flood prevention and pollution abatement from superfund sites
EPA Urban Waters Small Grants Program	Green infrastructure projects in urban areas that help reduce flooding, provide water quality benefits, and contribute to pollution abatement

More information on funding opportunities is available at the EPA Green Infrastructure Funding Opportunities page, or the National Wildlife Federation's Nature-Based Solutions Funding Database.

COMMON BARRIERS

Each NBS strategy summarized in Section 2 includes information on barriers and potential solutions that are particularly important for that specific strategy. There are also several barriers common across many of the NBS strategies covered in this document, which are reviewed below. Some of these barriers are not unique to NBS projects; however, it is important to acknowledge frequently cited barriers and the possible solutions that can be used to overcome them.

- **Cost:** NBS projects are perceived to be expensive; however, lifetime costs of implementing NBS strategies may be lower than gray infrastructure alternatives. Careful cost-benefit analysis, cost-effectiveness analysis, or similar approaches should be used for a holistic expense evaluation. NBS projects can be expensive, especially if they involve large-scale construction (e.g., river connectivity restoration, living shorelines) or work by technical experts (e.g., prescribed burns). However, nature-based solutions are frequently less expensive to install and operate than gray infrastructure projects that accomplish the same primary objectives, though the distribution of costs over time may differ (Van Zanten et al. 2023; Vineyard et al. 2015). Comparing the lifetime cost of the selected NBS strategy with alternative approaches can help to put the expense in perspective. Nature-based solutions also tend to create cobenefits, such as recreational opportunities, cleaner air or water, habitat, and carbon sequestration. While these cobenefits cannot always be quantified in monetary terms, it is important to recognize them as part of the cost-benefit balance of the project (Seddon et al. 2020; Van Zanten et al. 2023; Viti et al. 2022).
- **Capacity:** Lack of staff capacity to implement NBS projects is another frequently cited barrier (e.g., Schultz and Moseley 2021; Beaury et al. 2020), but new government programs are in place to help train a new and expanded workforce that can carry them out. Lack of capacity can be particularly challenging when strategies, such as

prescribed burns, require work by specially trained personnel. There is also a shortage of contractors with the required knowledge and skills to carry out some emerging NBS techniques, such as living shorelines or thin-layer placement for marsh restoration.

- **Public opinion:** Public opinion, either positive or negative, can drastically affect the efficiency and implementation of an NBS project. Negative public opinion of a project can slow down implementation or even stop it altogether, while positive public opinion can be a significant asset. Early, frequent, and transparent communication with the local community helps to avoid misunderstandings and address any concerns during project design and implementation. See the Community Engagement section for more details and best practices.
- **Conflict with other land uses:** While NBS implementation may conflict with other land uses, communicating the potential benefits and avoided risks provided in the long-term can help express why choosing a nature-based solution over another land use makes sense. Many NBS approaches require significant areas of land, which may displace or prevent other land uses from occurring. For example, there may be existing agricultural land along a river that would need to be restored for floodplain reconnection to occur, and installing living shorelines prevents future development directly along the coastline. However, the areas along these shorelines may be at heightened risk for flooding, erosion, or saltwater intrusion, making them less productive or useful lands. Depending on land ownership, these types of issues may increase project cost, raise local opposition to a project, or make a project infeasible to complete.
- **Regulation and permitting:** Like conventional projects, many NBS projects—especially those involving coastal habitats, wetlands, or waterways—require permits. The permitting process is frequently time-consuming and expensive, and specific requirements vary from state to state, making it difficult to provide relevant general guidance. However, identifying the permitting agencies and engaging in early and transparent communication can help to plan for the requirements for the specific project and avoid costly surprises later. Designing projects to be eligible for streamlined permitting processes, such as US Army Corps of Engineers (USACE) nationwide general permits, also helps to limit the time and cost required. See the Regulatory Processes section that follows for more details.
- **Lack of effectiveness evidence:** Some NBS strategies that have been in use for many years have sufficient effectiveness data, while others are less proven. However, there are efforts to gather and synthesize effectiveness data for a wide variety of NBS strategies to make them more accessible and easier to use. Information about a particular project's likely effectiveness, performance, and reliability is often needed to justify using a nature-based solution, especially in place of a gray infrastructure alternative. While some nature-based solutions are well-established and understood, others are newer or evolving and research on their outcomes is nascent or ongoing. There are many published studies for certain NBS strategies, but others lack strong supporting evidence. For these strategies, it is difficult to extrapolate results from one project or location to another, making it hard to know exactly how projects will perform and what cobenefits will be achieved. Monitoring and evaluation of project performance using a common set of credible metrics is key to filling critical evidence

gaps, providing information needed for adaptive management, and ensuring projects achieve satisfactory and measurable results (Conroy et al. 2011). Applying adaptive management designed to test and iterate on design and management of less-established nature-based solutions, can help manage uncertainty and build knowledge on how to best design and build these projects.

REGULATORY PROCESSES

NBS projects often involve alterations to habitats, such as wetlands, that are protected at the federal, state, and sometimes local levels. Therefore, projects are subject to various regulatory processes. Because state and local regulations vary widely, it is not possible to provide comprehensive general information about regulatory and permitting requirements. This section reviews the federal regulations most relevant to NBS projects. Individual DOI bureaus and offices may have additional requirements for projects on their lands, which are not covered here.

- **NEPA review:** NBS projects planned and executed by DOI, including planning and implementation efforts such as BLM Range Management Plans and USFWS Comprehensive Conservation Plans, are subject to NEPA requirements. For projects that do not fall under a categorical exclusion (described later), NEPA requires an environmental assessment to determine if the proposed action is likely to have a significant environmental impact and, if so, an environmental impact statement with more detailed information on the environmental impact of the proposed action and any alternatives (43 CFR 46.300, 43 CFR Part 46 Subpart E). DOI supports the use of existing NEPA analyses where the data and assumptions used are relevant for the proposed action to reduce the NEPA workload (43 CFR 46.120). Proposed updates to NEPA implementation, released for public comment in July 2023, aim to make the NEPA process more efficient by encouraging programmatic environmental reviews that address multiple projects or categories of projects; enabling agencies to establish new categorical exclusions for certain contexts, geographies, and project types; and allowing agencies to use existing analyses in environmental reviews (88 FR 49924). Several NBS strategies—hazardous fuels reduction, including prescribed fire and mechanical methods, and post-fire rehabilitation activities such as tree planting and habitat restoration—are already categorically excluded from detailed NEPA analysis if they meet certain parameters related to the acreage treated, location, and potential for public health effects (43 CFR 46.210, 43 CFR 46.215).
- **USFWS species permitting:** For any project that may affect a listed (endangered) species or designated habitat, consultation with the USFWS is required. Informal consultation early in the project planning process is encouraged; USFWS field offices can provide technical assistance to identify listed species that may be present and what effect the project may have on those species. If required, a formal consultation later on will include a biological opinion analyzing the effects of the proposed project on the species or habitat and recommending measures to minimize those effects. Other wildlife relevant regulations to be aware of include the Fish and Wildlife Coordination Act (FWCA) (16 U.S.C. 661-666(e)) and the Migratory Bird Treaty Act (MBTA) (16 U.S.C. 703-712). The FWCA directs the USFWS to investigate federal actions that might affect wildlife resources, and the MBTA enforces international treaties that help ensure

sustained populations of migratory bird species. NBS projects that may impact wildlife habitat and/or result in take of protected migratory birds will need to work with the USFWS to ensure they are in compliance with these regulations.

- **USACE permitting:** The USACE has authority under multiple statutes (Clean Water Act Section 404; Marine Protection, Research, and Sanctuaries Act; Rivers and Harbors Act of 1899) to regulate actions that are part of many NBS projects, including changes to dams or dikes in navigable waters; excavation, dredging, or disposal in navigable waters; any actions that modify the condition, course, or location of a navigable waterway; and discharges of dredged or fill material into waterways (33 CFR Part 320). Depending on the specific project and location, an individual permit may be required, or there may be an applicable general permit that authorizes the activity as long as certain conditions are met. General permits are intended to provide a quicker, more streamlined approval process and may be applicable nationally or only in certain regions or states (33 CFR Part 330). There are currently two nationwide permits most relevant to NBS projects: the nationwide permit for living shorelines, which authorizes living shorelines up to 500 ft in length (this general permit is currently not in effect in the New England USACE district) (Nationwide Permit 54), and the nationwide permit for aquatic habitat restoration, enhancement, and establishment, which authorizes a variety of restoration activities in aquatic habitats that increase ecosystem function, among other requirements (Nationwide Permit 27).
- **NOAA coastal and marine regulations:** There are protections in place for coastal and marine habitats and species that may require more permitting and review for projects in those areas. The Magnuson-Stevens Fishery Conservation and Management Act protects areas designated as essential fish habitat and requires federal agencies to consult with NOAA Fisheries to avoid, reduce, or compensate for any adverse effects to these habitats. Projects that may impact marine mammals, protected under the Marine Mammal Protection Act, should also consult with NOAA Fisheries about an incidental take authorization. NOAA Fisheries has jurisdiction over listed marine and anadromous species, so projects that may impact threatened or endangered marine species are also subject to ESA consultations. In coastal areas, the Coastal Zone Management Act has been used to establish coastal management programs that act as a permitting and regulatory framework that can help encourage coastal habitat restoration and other similar nature-based solutions (Karasik et al. 2022).
- **FEMA floodplain standards:** Any project built in a floodplain must obtain a development permit, and projects in the regulatory floodway must go through an encroachment review to ensure they do not increase the flood hazard to downstream properties or communities. These standards are required by FEMA as part of the National Flood Insurance Program, but are implemented by local governments (FEMA 2005).
- **Additional regulations for projects with specific potential impacts:**
    - For any project located near a historic property, the National Historic Preservation Act of 1966 (NHPA) requires that federal agencies identify and assess the effects their actions may have on historic properties (as defined in the NHPA). This involves consultation with the State Historic Preservation Officer and/or Tribal

Historic Preservation Officer (as well as local governments and other interested stakeholders) to identify properties potentially affected and develop alternatives to minimize, mitigate, or avoid these effects.

- For any project that will discharge pollutants from a point source, such as constructed wetlands that treat wastewater, a National Pollutant Discharge Elimination System (NPDES) permit is required. Construction activities that disturb more than an acre of land may also be required to obtain an NPDES permit for stormwater discharge. There is a Construction General Permit available for states where the EPA is the permitting authority; many states administer their own NPDES permitting programs and may have additional regulatory conditions.
- For projects implemented by non-DOI partners on DOI lands, special use permits from the relevant DOI bureau may be required—for example, National Park Service special use permits or USFWS special use permits. For any project that might impact a river in the Wild and Scenic Rivers System, the Wild and Scenic Rivers Act needs to be considered. This Act requires the protection and enhancement of water quality and other outstanding remarkable values of the protected river.
- For any project that might impact a designated wilderness area, the protections of the Wilderness Act need to be considered.
- For any project that may impact archaeological resources, the protections of the Archaeological Resources Protection Act need to be considered.

GRAY INFRASTRUCTURE ALTERNATIVES

Nature-based solutions are sometimes used as an alternative to gray infrastructure to solve a specific socioenvironmental challenge. A nature-based solution may be a direct substitute for gray infrastructure, such as installing a living shoreline instead of an artificial breakwater, or used in combination with gray infrastructure, like a bioswale. A nature-based solution can represent an alternative approach that addresses the issue in a fundamentally different way than gray infrastructure, such as floodplain reconnection to address downstream flooding rather than installation of a levee and dike system. When used in suitable contexts and designed properly, nature-based solutions can be as effective as gray infrastructure alternatives and frequently provide more cobenefits while requiring less maintenance. However, it is important to recognize that nature-based solutions cannot always replace gray infrastructure and that efficacy depends on the project's location, design, and successful implementation and maintenance over time. Adaptive management provides a process to assess project efficacy, learning from successes and failures to improve future NBS project designs and outcomes.

Tables A.2–A.6 provide information about nature-based solutions and gray infrastructure alternatives with similar primary objectives; each table applies to a different primary objective (coastal erosion and flooding, stormwater management, urban heat, aquifer recharge, and riverine flooding).

Table A.2 Comparison of NBS (in green) and gray (in gray) infrastructure strategies to address coastal erosion and flooding

Installation Cost	Maintenance Needs	Outcomes	Site Suitability
Beach nourishment			
$1.1 million per mile of shoreline (TGLO n.d., NOAA 2020), equivalent to about $200 per linear foot. This is an average value and costs can vary widely based on the technique used and the sediment source. An economic analysis of beach nourishment projects in North Carolina found an average cost of $4.73/y3 of sediment, but the maximum was more than $11/y3 (Qiu et al. 2020).	Beach nourishment needs to be done repeatedly (every 2 to 10 years) since it does not mitigate the cause of erosion (Staudt et al. 2021).	Protects coast against severe storms, mitigates coastal flooding, attenuates waves, protects communities, stimulates tourism and the local economy.	Gently sloping beaches with minor upland erosion. Usually done on beaches with significant recreational use. Not suitable near seagrass or mangroves or where sand migration will inhibit boat navigation.
Coastal marsh restoration			
$16,000–$2,000,000 per acre (Wang et al. 2022; NOAA 2020) or $78–$286 per linear foot (NOAA 2020). Costs per acre are much less for larger projects (Wang et al. 2022).	Invasive species removal, occasional replanting, and sediment remediation as needed.	Reduces erosion and coastal flooding, attenuates waves, can gain elevation with sea level rise, enhances habitat and biodiversity.	Most effective in less-developed areas so there is sufficient area available for restoration and sediment accretion processes are not impeded.
Coral reef restoration			
$739,535–$1,165,651 per acre (Bayraktarov et al. 2016). NOAA estimates up to $25 million per acre (2020).	Invasive species removal, repair after severe storms, maintaining coral nursery, cleaning metallic tools and dive equipment used for maintenance.	Wave attenuation, storm surge mitigation, enhanced water quality. Can gain elevation with sea level rise. Increased biodiversity, fish harvest, recreation, and tourism.	Requires hard, stable substrates and good light penetration. Most successful near existing coral populations or where coral reefs were historically present.
Dune restoration			
$2,000–$5,000 per linear foot (NOAA 2020).	Invasive species removal, repairing sand fences and boardwalks after severe storms, watering plants in dry climates, restricting beach grooming. Periodic renourishment may be necessary if erosion is high. $100–$500 per linear foot per year (NOAA 2020).	Protection from storms, wave attenuation, less frequent overwashing, coastal flood mitigation, increased resilience to sea level rise, increased biodiversity. Can limit beach access.	Most successful near existing dunes in windy conditions. Should not be built on narrow beaches or adjacent to seawalls, bulkheads, and groins that cause dune erosion. Frequently combined with beach nourishment projects.

Table A.2 Comparison of NBS (in green) and gray (in gray) infrastructure strategies to address coastal erosion and flooding *(continued)*

Installation Cost	Maintenance Needs	Outcomes	Site Suitability
Living shoreline			
$117–$603 per linear foot (NOAA 2020).	Invasive species and debris removal, replanting vegetation, adding sand fill as needed. Up to $100 per year per linear foot (SAGE et al. 2015).	Reduces erosion and wetland loss, enhances tidal habitats, restores natural sediment and nutrient exchanges. Limited floodwater absorption and high-water protection.	Suitable for low-to-medium wave energy environments.
Mangrove restoration			
$2,000–$45,000 per hectare for planting; $4,000–$141,000 per hectare for hydrological restoration (median cost) (Beck et al. 2022).	Removal of trash and debris that inhibit growth, minor hydrological repairs as needed to maintain tidal flows, controlling grazing if relevant, continued distribution of mangrove propagules/seedlings.	Reduces coastal flooding and attenuates waves. May be able to gain elevation with sea level rise, to a point. Sequesters carbon, increases habitat and biodiversity. Requires more land area than gray alternatives.	Hydrologic conditions must be suitable for mangrove growth. Not as effective in heavily developed areas.
Oyster bed restoration			
Ranges from average of $48,650 per acre for structurally simple projects to $508,332 per acre for structurally complex projects (Bersoza Hernández et al. 2018). $203–$386 per linear foot (NOAA 2020).	Invasive species removal, replacing cultch material (structurally simple projects only) if oyster bed is not keeping up with sediment accretion (Coen et al. 1999).	Wave attenuation, protection from coastal flooding, reduced shoreline erosion, increased shellfish harvest, improved water quality. Benefits adjacent habitats (marshes, seagrasses, mangroves).	Often used with living shoreline projects. Most successful near healthy shellfish populations in waters at least one foot deep at low tide with a hard substrate.
Seagrass restoration			
$244,634–$4,695,002 per acre (Paling et al. 2009); $38,000–$2,800,000 per acre (NOAA 2020).	Removal of invasive species and bioturbators, limiting boat traffic near site, reducing nutrient pollution reaching site.	Wave attenuation, reduced erosion, sediment stabilization, increased water clarity. Enhanced biodiversity, fish harvest, recreation and tourism.	Not suitable for high wave energy environments. Requires high light availability.

Table A.2 Comparison of NBS (in green) and gray (in gray) infrastructure strategies to address coastal erosion and flooding *(continued)*

Installation Cost	Maintenance Needs	Outcomes	Site Suitability
Artificial breakwater			
$5,000–$10,000 per linear foot (NOAA 2015).	Invasive species removal, replacing dislodged stones, filling gaps, removing rubble. $500+ per linear foot per year (NOAA 2015).	Reduces wave energy and mitigates storm surge. Protects wetlands. No high-water protection.	Suitable for low to medium wave energy environments. Often used near marinas.
Bulkhead			
$2,000–$5,000 per linear foot (NOAA 2015).	Erosion mitigation, sealing cracks, replacing materials. Maintenance frequency varies but is often needed after experiencing medium to high wave energy. About $100–$500 per year per linear foot (NOAA 2015).	Moderates wave action, limits changes in water level between tides. Causes erosion of seabed and adjacent areas, loss of intertidal habitat, and limited sediment transport.	Suitable for high-energy environments, often paired with docks or developed waterfront infrastructure.
Dike			
$8,780* per linear foot (Aerts 2018).	Vegetation control, debris removal, erosion control, animal burrow removal, pump replacement, addressing seepage issues.	Flood control, reduces wave energy, provides storm surge protection, increases ship navigability. Can be breached by high waters, disconnects rivers from floodplains, prone to erosion from water or ice.	Often combined with wetlands to form green-gray tiered flood protection infrastructure.
Groin			
$2,000–$5,000 per linear foot (NOAA 2015).	Erosion control, replacing materials, restoring substrates at adjacent sites. About $100–$500 per linear foot per year (NOAA 2015).	Protects from waves but does not provide high-water protection. Causes erosion of adjacent sites and detrimental impacts to shoreline ecosystem.	Often paired with beach nourishment.

Table A.2 Comparison of NBS (in green) and gray (in gray) infrastructure strategies to address coastal erosion and flooding *(continued)*

Installation Cost	Maintenance Needs	Outcomes	Site Suitability
Riprap/revetment			
\$5,000–\$10,000 per linear foot (NOAA 2015).	Erosion mitigation, filling holes in rocks, maintaining structure height, repairing damaged caused to adjacent areas. About \$100–\$500 per year per linear foot (NOAA 2015).	Moderates wave action, prevents slope erosion. Causes loss of intertidal habitat, erosion of adjacent areas, and limited sediment transport. Does not provide high-water protection.	Usually paired with preexisting gray or hardened structures.
Seawall			
\$5,000–\$10,000 per linear foot (NOAA 2015).	Erosion control, vegetation removal, repairing cracks and sinkholes, cleaning weepholes. \$500+ per year per linear foot (NOAA 2015).	Moderates wave action even in high-energy environments, prevents storm surge. Causes seabed erosion and loss of intertidal habitats. Limits sediment transport.	Suitable for areas with high wave energy and storm surge risk.

Installation costs are provided as a range or average cost where that information was available, but are sometimes examples from individual projects (marked with an asterisk *). See NBS strategy summary sections for more information on outcomes and site suitability.

Table A.3 Comparison of NBS (in green) and gray (in gray) infrastructure strategies to address stormwater management

Installation Cost	Maintenance Needs	Outcomes	Site Suitability
Built wetlands			
Approximately \$48,000–\$100,000 per acre (US EPA 1999, converted from 1998 to 2022 dollars).	Keeping inlets and outlets clear, removing debris and accumulated sediment, invasive species removal.	Improved water quality, reduced flooding, drought mitigation, aesthetics, recreational opportunities, wildlife habitat.	Should be located outside of a floodplain or intact wetland complex to avoid degrading aquatic resources (EPA 2000).
Nontidal wetland restoration			
\$1,389* per acre (ephemeral wetlands, Biebighauser 2002).	Invasive species removal, clearing debris from spillway, mowing and repairing ditch plugs as needed.	Flood mitigation, temperature reduction, drought mitigation via aquifer recharge, reduced water pollution.	Flat areas with indicators of past wetland presence, including low-lying, frequently flooded areas and hydric soils.

Table A.3 Comparison of NBS (in green) and gray (in gray) infrastructure strategies to address stormwater management *(continued)*

Installation Cost	Maintenance Needs	Outcomes	Site Suitability
Stream restoration			
$500–$1,200 per linear foot (Kenney et al. 2012).	Invasive species removal, debris removal after high flows, replanting buffers if erosion is occurring, replacing lost woody debris.	Flood protection, reduced bank erosion, drought mitigation and aquifer recharge, enhanced water quality and habitat diversity. May require tree loss in heavily forested areas.	Projects are most successful in low-gradient streams with cohesive banks (clay or silt sediments) and natural flows. Low success rates are a problem for stream restoration, with less than half of projects considered ecologically successful (Alexander and Allan 2007).
Urban greening			
Tree planting: $12.87–$288 per tree (McPherson et al. 2005; NOAA 2020). Green roofs: $10–$40 more per square foot than conventional roofs (Department of Energy and Environment 2018), $9–$31 per square foot total (NOAA 2020).	Tree maintenance can cost $15–$81 per tree per year (NOAA 2020). Weed control, irrigation, fertilization, and replanting of green roofs ($0.02–$0.41 per square foot per year [NOAA 2020]).	Improved air and water quality, rainfall interception and stormwater management, enhanced infiltration, enhanced community engagement and human health, urban cooling and reduced energy demands.	Tree species should be selected for the site. Avoid areas immediately near overhead wires and underground utilities to provide room for growth. Green roofs are most beneficial in built-up urban areas with large amounts of impervious surfaces and easiest to build on larger concrete roofs of new construction.
Urban stormwater and runoff management			
Rain garden: $5–$16 per square foot. Bioswale: $5.50–$24 per square foot. Vegetated filter strips: $0.03–$3 per square foot. Permeable pavers, porous concrete or asphalt: $5.50–$12 per square foot (NOAA 2020).	Rain garden: $0.31–$0.61 per square foot per year. Bioswale: $0.06–$0.21 per square foot per year. Vegetated filter strips: $0.07 per square foot per year. Permeable pavers, porous concrete, or asphalt: $0.01–$0.23 per square foot per year (NOAA 2020).	Flood mitigation, drought mitigation, heat mitigation, improved water quality.	Urban areas (different techniques have varying space requirements); steep slopes not suitable for some techniques. Permeable pavement only suitable for low-traffic areas.
Stormwater drainage system			
Retention area: $24.80–$50.60 per square meter. Urban sewer pipe: $61–$861 per meter (Aerts 2018).	Clearing debris and sediments out of pipes and drains after rainfall, repairing mechanical cleaning devices, cleaning pump systems, repairing degraded or clogged pipes.	Manages runoff from impervious surfaces, mitigates inland flooding, may remove pollutants if stormwater is treated. Often overwhelms water bodies at discharge points.	Can be paired with urban stormwater and runoff management NBS strategies (rain gardens, bioswales, permeable pavement) to create green-gray hybrid system.

Installation costs are provided as a range or average cost where that information was available, but are sometimes examples from individual projects (marked with an asterisk *). See NBS strategy summary sections for more information on outcomes and site suitability.

Table A.4 Comparison of NBS (in green) and gray (in gray) infrastructure strategies to address urban heat

Installation Cost	Maintenance Needs	Outcomes	Site Suitability
Urban greening			
Tree planting: \$12.87–\$288 per tree (McPherson et al. 2005, NOAA 2020). Green roofs: \$10–\$40 more per square foot than conventional roofs (Department of Energy and Environment 2018).	Tree maintenance can cost \$15\$–81 per tree per year (NOAA 2020). Weed control, irrigation, fertilization, and replanting of green roofs may cost \$0.02–\$0.41 per square foot per year (NOAA 2020).	Urban cooling and reduced energy demands, estimated at \$20.10/m^2 over a 50-year lifespan compared to a conventional roof (Sproul et al. 2014). Urban vegetation provides additional benefits including improved air and water quality, rainfall interception and stormwater management, enhanced infiltration, enhanced community engagement and human health,	Tree species should be selected for the site. Avoid areas immediately near overhead wires and underground utilities to provide room for growth. Green roofs are most beneficial in built-up urban areas with high impervious surface and easiest to build on larger concrete roofs of new construction.
Cool roof coating			
Typically costs about \$0.10–\$0.20 per square foot more than conventional roofs (US EPA 2008).	Rinsing off sediment or particulates to maintain reflectance.	Reduce heat island effects and energy demand. Can save \$8.90/m^2 over a 50-year lifespan in energy demand compared to conventional roofs (Sproul et al. 2014).	More suitable than green roofs for lower-budget projects where the primary goal is energy savings (US EPA 2014).

Installation costs are provided as a range or average cost. See NBS strategy summary sections for more information on outcomes and site suitability.

Table A.5 Comparison of NBS (in green) and gray (in gray) infrastructure strategies to address aquifer recharge

Installation Cost	Maintenance Needs	Outcomes	Site Suitability
Nontidal wetland restoration			
\$1,389 per acre (ephemeral wetlands, Biebighauser 2002).	Invasive species removal, clearing debris from spillway, mowing and repairing ditch plugs as needed.	Flood mitigation, temperature reduction, drought mitigation via aquifer recharge, reduced water pollution.	Flat areas with indicators of past wetland presence including low-lying frequently flooded areas and hydric soils.
Artificial aquifer recharge			
\$90–\$1,100 per acre foot of water stored (Choy et al. 2014); project capital costs total \$200,000–\$3,600,000 (Vanderzalm et. al. 2022).	Removing physical clogs and biomass growth near or in pipes, repairing mechanical issues with recharge wells and gas pores, repairing corroded pipes. Yearly operating costs of \$20,000–\$260,000 (Vanderzalm et. al. 2022).	Recharges aquifers, counteracts land subsidence, limits saltwater intrusion into groundwater. Can become a source of groundwater contamination.	Usually used to recharge deep aquifers where surface application of water does not reach the aquifer.

Installation costs are provided as a range or average cost. See NBS strategy summary sections for more information on outcomes and site suitability.

Table A.6 Comparison of NBS (in green) and gray (in gray) infrastructure strategies to address riverine flooding

Installation Cost	Maintenance Needs	Outcomes	Site Suitability
Floodplain reconnection			
$1,295–$2,590 per acre of floodplain (Gourevitch et al. 2020). This does not include costs of floodplain buyouts or dam removal, which may be needed for some projects.	Removing invasive species and clearing understory vegetation, repairing log jams and submersible check dams as needed after heavy rainfall, periodically redredging side channels.	Flood protection, reduced erosion, drought mitigation, carbon sequestration, increased biodiversity, enhanced water quality. Uses more land area than gray infrastructure alternatives.	Relatively flat floodplain area adjacent to a river with near-natural flow, with ample space between river and development.
Riparian buffer restoration			
$4,000–$8,000 per river mile (Bair 2005).	Invasive species removal, periodic mowing, removing debris, erosion control as needed, repairing fences if overgrazing is an issue, mulching to retain water, replanting native plants as needed.	Flood protection, reduced erosion, enhanced water quality, urban cooling, increased biodiversity and recreational opportunities.	Most beneficial in areas adjacent to sources of pollution where stream or riverbanks are sparsely vegetated or experiencing erosion.
Stream restoration			
$500–$1,200 per linear foot (Kenney et al. 2012).	Invasive species removal, debris removal after high flows, replanting buffers if erosion is occurring, replacing lost woody debris.	Flood protection, reduced bank erosion, drought mitigation and aquifer recharge, enhanced water quality and habitat diversity. May require tree loss in heavily forested areas.	Projects are most successful in low-gradient streams with cohesive banks (clay or silt sediments) and natural flows. Low success rates are a problem for stream restoration, with less than half of projects considered ecologically successful (Alexander and Allan 2007).

Table A.6 Comparison of NBS (in green) and gray (in gray) infrastructure strategies to address riverine flooding *(continued)*

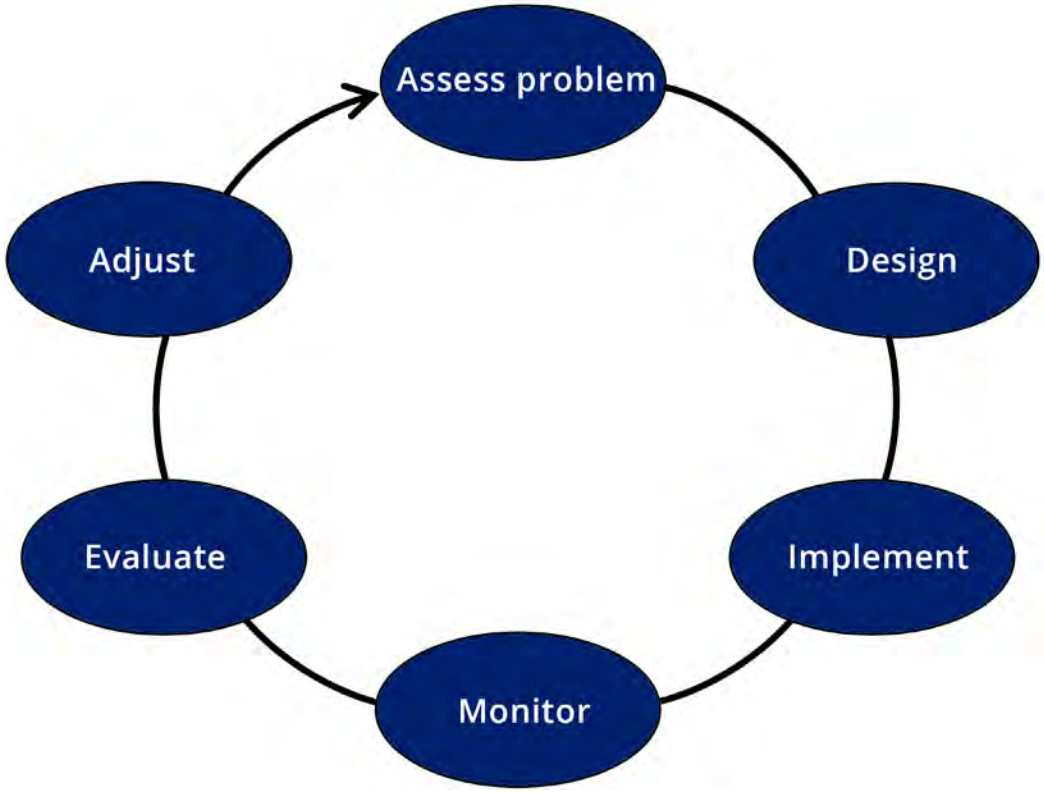
Installation Cost	Maintenance Needs	Outcomes	Site Suitability
Dam construction			
$587–$3,045 per million liters of reservoir storage (Pertheram and McMahon 2019).	Mowing and debris removal, remediating erosion, filling cracks in concrete dams, removing debris and sediment from spillways, repairing broken valves and electrical equipment as needed. Average lifespan is 50 years (MIT 2012); dams are often removed when maintenance costs exceed removal cost.	Reduces flood severity and frequency, provides water storage and can produce hydroelectric power. Converts large land areas into a reservoir, reduces downstream sediment transport and river connectivity. Reservoirs frequently have eutrophication and algal bloom issues.	Many dams in the United States were built to provide water storage or hydroelectricity; some are no longer needed for these purposes.
Levee and dike system			
$10.9–$16.8 million per kilometer (Aerts 2018).	Vegetation control and mowing, debris removal after major storms, erosion control and removing animal burrows as needed, pump replacement every 7–10 years, addressing seepage problems.	Flood control, increases ship navigability, increases area of arable or developable land along river. Disconnects rivers from floodplains, can be breached by high waters, increased water speed in main channel.	Often used to protect developed or agricultural land along rivers from flooding. Levee placement can be set back from river to allow space for floodplain accommodation.

Installation costs are provided as a range or average cost. See NBS strategy summary sections for more information on outcomes and site suitability.

ADAPTIVE MANAGEMENT AND MONITORING

Adaptive management is important for the implementation of NBS projects. *Adaptive management* is a flexible project implementation process used when there are uncertainties associated with a management decision. Adaptive management is generally viewed as a cycle that involves planning, implementation, and monitoring outcomes so that appropriate management adjustments can be made if necessary (Williams et al. 2007; Figure A.1). This form of adaptive management has been called *passive*, whereas *active* adaptive management involves a semiexperimental project design that includes planning and implementing varied management techniques, monitoring those varied management strategies, and revised action that implements the management variation that results in the greatest level of desired outcomes (National Research Council 2004). It will be beneficial for DOI to implement active adaptive management where possible to test different variations of NBS strategies. DOI policy on implementation of adaptive management ensures that adaptive management is considered in its policies, plans, guidance documents, agreements, and other instruments for the management or costewardship of resources under the department's jurisdiction (DOI 2023).

Figure A.1 The adaptive management process



Adapted from Williams et al. 2007.

NBS projects should be monitored to ensure that the desired outcomes and cobenefits for both nature and people occur. Where they are not, the project should be reevaluated and adjusted to ensure optimal outcomes are achieved. It is important to select metrics that measure all desired project outcomes. These metrics should be selected during the planning and design stage of a project, using the decision context and identified uncertainties to determine which metrics to measure and how they will be measured (scale, temporal frequency, sampling intensity, and others) (Marcot et al. 2012). Monitoring costs should be factored into the project budget. Future project adjustments need to be considered in maintenance and operations plans as well. If there is a risk of high costs to adjust the management approach, a financial assurance mechanism, such as a trust, can be used to ensure appropriate adaptive management can be applied.

For more information on adaptive management, see existing DOI materials including the DOI Adaptive Management Technical Guide (Williams et al. 2009), the DOI Adaptive Management Application Guide (Williams and Brown 2012), and the DOI Adaptive Management Policy (2023).

OPERATIONS AND MAINTENANCE

NBS projects frequently have lower operations and maintenance costs than gray infrastructure alternatives—in fact, lower costs is one of the primary reasons cited by companies that implement nature-based solutions (The Nature Conservancy's Business Council 2019). However, NBS projects do require maintenance to perform as intended, so it is important to develop an operations and maintenance plan along with the project design and ensure that adequate funding for operations and maintenance is included in the project budget.

Common NBS maintenance activities focus on maintaining the desired site and vegetation conditions to facilitate adequate ecosystem function. Specific activities may include invasive species removal, pest and disease control, debris removal, slope stabilization, and maintenance of project boundaries to avoid foot or vehicle traffic (Inter-American Development Bank 2020). These activities will likely be required more frequently soon after project construction, especially if the project involved planting young plants that need time to establish and grow.

Key aspects of an operations and maintenance plan include a list of which actions need to be performed and at what frequency, considering how seasonal variability may influence requirements; adequate funding and trained personnel to carry out maintenance; and contingency plans for maintenance schedules in case of extreme events that require additional inspection or maintenance.

CROSS-CUTTING BENEFITS

Three common benefits of NBS implementation were identified that span multiple NBS strategies:

Supporting Native Plant Species

Many NBS strategies are intended to improve conditions to support native plant species—for example, by restoring hydrologic or geomorphic conditions to match native plants' needs, removing invasive plants or pests that threaten native species' survival, and directly planting native vegetation. Native plants have many ecological benefits compared to nonnative (even if noninvasive) plants (USFS n.d.). Some native species require less water than nonnative plants, making them more resilient to drought and less likely to reduce water availability for nearby natural or human communities. They are also less vulnerable to fire than many invasive plants, which contribute to high-severity wildfires in the western United States (Brooks et al. 2004). Native plants also provide habitat to other native species and therefore contribute to overall ecosystem health (USFS n.d.). Therefore, it is important to select native plants whenever revegetation is required as part of an NBS project, even if native plants are not a focus of the project.

There are many resources available to help select native plants suitable for a particular site. The USDA PLANTS tool includes many filters such as nativity status, state, growth requirements (shade, precipitation, drought tolerance, soil texture, and more), height, and flowering season. There are also tools to identify plants that benefit certain wildlife, such as butterflies (National Wildlife Federation Native Plant Finder) or birds (Audubon Native Plants Database). Many state agencies also have native plant guides specific to their region (e.g., Michigan State University Plant Search Tool, Virginia Native Plant Finder). It is important to incorporate future climate projections when identifying the right native species to plant. As climate continues to shift, the appropriate habitat range for species will too. Resources for considering climate shifts when selecting species included the USDA Forest Service (USFS) Climate Change Tree Atlas, USDA Seedlot Selection Tool, and USFS Plant Species and Climate Profile Predictions.

Avoided Habitat Conversion/Loss

DOI plays a vital role in the federal America the Beautiful initiative, which aims to conserve, connect, and restore 30% of US lands and waters by 2030. Conserving and enhancing native habitats is an explicit goal of many of the NBS strategies included in this Roadmap. For example, assisted marsh migration is intended to preserve the total area of coastal marsh as some existing marsh is lost to sea level rise, thinning reduces the risk of catastrophic wildfire that can wipe out forested areas, and prescribed fire maintains native grasslands. While each DOI bureau has a different mission and approach to land conservation and management, all have opportunities to contribute to enhanced land management and reduce habitat loss.

Box 4. Examples of DOI Keystone Species Management

- North American beavers are ecosystem engineers that alter landscape hydrology when they create dams. Beaver management can have drastic effects on how water moves through an ecosystem and even what habitats are able to establish. For example, in some areas beaver ranges are expanding with climate change and beaver management might be needed to allow historic ecosystems to persist.
- NPS has set up an alert system to notify the public of a newly identified fungal disease called rapid ʻōhiʻa death (ROD) that is killing ʻōhiʻa trees. The ʻōhiʻa flower is a keystone species providing food for numerous endemic Hawaiian birds. NPS is tracking existing ROD cases and amplifying public guidance for how to avoid the spread of the disease and protect the ʻōhiʻa.
- Wolves, a keystone predator, were locally extirpated from Yellowstone National Park in the early 1900s. In 1995, wolves were reintroduced to the park. Almost 30 years later, habitats have changed dramatically (in part resulting from wolf-related control of herbivores), and there is evidence that Yellowstone biodiversity has increased as a result of the wolf reintroduction (NPS n.d., Smith and Peterson 2021).

Protecting Keystone Species

Keystone species are those that are essential for an ecosystem to function. When a keystone species declines or is removed completely from an ecosystem, it sets off a chain reaction that can dramatically alter the structure and functioning of an ecological community and can even cause ecosystem collapse. These species are not necessarily the most abundant in a particular system, but they play a disproportionately large role in the sustainability of an ecosystem (Denchak 2019, Wagner 2010). Conservation, management, or reintroduction of keystone species are important for maintaining or reestablishing ecosystem structure and function (Wagner 2010). Nature-based solutions may directly affect keystone species (e.g., beaver management or invasive and nuisance species removal) or focus on enhancing habitat to support keystone species.

DOI has been involved in managing keystone species for decades and will continue to do so. Keystone species management helps the natural or modified ecosystems managed through nature-based solutions to function as intended (Box 4).

CONCLUSION

The cross-cutting considerations for NBS projects described here can help to inform project selection and design. However, more specific information on siting, design, construction, and expected benefits of particular NBS strategies, provided in Section 2, is needed to support decision-making. Therefore, the information presented in this section is intended to be used alongside the NBS strategy-specific summaries that follow.

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Section 2
Nature-Based Solutions Strategy-Specific Content

Section 2 of the Roadmap includes detailed summaries on individual NBS strategies, including the following:

- **Definition** of the nature-based solutions (NBS) strategy
- Overview of the **technical approach** to implementing the NBS strategy, including factors influencing **site suitability**
- Project **operations and maintenance** needs and lists of **gray infrastructure approaches** for which the NBS strategy may provide an alternative
- Key **tools, training, and resources** for project planning, implementation, and monitoring
- **Likely benefits and outcomes** of the NBS strategy for both people and nature, categorized into (1) climate threat reduction, (2) social and economic, and (3) ecological benefits. It also includes explanations of how the strategy creates these benefits (primary objectives for each strategy are highlighted).
- **Barriers and solutions** to implementing the NBS strategy
- **Example projects** from throughout the United States, highlighting Department of the Interior (DOI) involvement, with information on techniques used, project size and cost, and adaptive management lessons learned

The full list of NBS strategies included in this Roadmap can be found in the Table of Contents that follows. There are several approaches to navigate the strategy-specific content and find information about strategies that align with management objectives:

- By strategy and habitat type, using the table of contents that follows
- Using the index linking alternative terms used for nature-based solutions projects with strategies included in the Roadmap (Table B.1)
- By challenge addressed or targeted outcomes (Tables B.2–B.4 for climate threat reduction, ecological, and social and economic outcomes)

These summaries do not cover all possible types of NBS projects but are a subset of NBS strategies most relevant to DOI management, selected through conversations with DOI personnel. Other NBS strategies, including agricultural best management practices, may be used by DOI in certain contexts but have not been included in this version of the Roadmap.

NATURE-BASED SOLUTIONS STRATEGY SUMMARIES

Table B.1 Index of NBS terms to Roadmap strategy summaries

Common NBS Term	Roadmap Strategy Summary
Beach restoration	Beach nourishment Dune restoration
Bioswales	Urban stormwater and runoff management
Constructed wetlands	Built wetlands
Coastal wetland restoration	Coastal marsh restoration Mangrove restoration
Culvert replacement or removal	Riverine connectivity restoration Floodplain reconnection
Dam removal	Riverine connectivity restoration Floodplain reconnection
Fish passage	Riverine connectivity restoration
Fuel management	Prescribed burns Thinning
Green roofs	Urban greening
Green stormwater infrastructure	Urban stormwater and runoff management
Greenways/parks	Urban greening
Inland wetland restoration	Nontidal wetland restoration
Integrated pest management	Invasive and nuisance pest and pathogen removal Invasive and nuisance plant species removal
Levee setback/removal	Floodplain reconnection
Low-impact development	Urban stormwater and runoff management
Permeable pavement	Urban stormwater and runoff management
Pollinator gardens	Urban greening
Prairie restoration	Grassland conservation and restoration
Rain gardens	Urban stormwater and runoff management
Rainwater harvesting	Urban stormwater and runoff management
Reforestation	Forest conservation and restoration

Table B.1 Index of NBS terms to Roadmap strategy summaries *(continued)*

Common NBS Term	Roadmap Strategy Summary
Rock detention structures	Nontidal wetland restoration
Salt marsh restoration	Coastal marsh restoration
Small island creation	Beach nourishment
Stormwater parks	Urban stormwater and runoff management
Submerged aquatic vegetation restoration	Seagrass restoration
Submersible check dams/logjams	Floodplain reconnection
Tree trenches	Urban stormwater and runoff management
Treatment wetlands	Built wetlands
Upslope marsh migration	Assisted marsh migration
Urban forestry	Urban greening
Wildland-urban interface management	Green firebreaks
Wildlife overpasses/underpasses	Wildlife road crossing structures

There are many different names used to refer to NBS project types, including broad terms (e.g., *green stormwater infrastructure*) and more specific terms (e.g., *rain gardens*). This table shows where to find information on various NBS terms in the Roadmap strategy summaries. For example, information on rain gardens is included in the urban stormwater and runoff management strategy.

Table B.2 NBS strategies by expected implementation benefits and outcomes related to climate threat reduction

NBS Strategy	Reduced Flooding	Carbon Storage and Sequestration	Reduced Wildfire Risk	Drought Mitigation	Sea Level Rise Adaptation and Resilience	Heat Mitigation	Storm Protection	Improved Air Quality
Assisted marsh migration	✓	—	—	—	✓	—	✓	—
Beach nourishment	✓	—	—	—	✓	—	✓	—
Beaver management and beaver analogs	✓	✓	✓	✓	—	✓	—	—
Built wetlands	✓	—	—	✓	—	—	—	—
Coastal marsh restoration	✓	✓	—	—	✓	—	✓	—
Coral reef restoration	✓	✓	—	—	✓	—	✓	—
Dune restoration	✓	✓	—	—	✓	—	✓	—
Floodplain reconnection	✓	✓	✓	✓	—	✓	—	—
Forest conservation and restoration	✓	✓	✓	—	—	✓	—	✓
Grassland conservation and restoration	—	✓	—	—	—	—	—	—
Green firebreaks	—	—	✓	—	—	—	—	✓
Invasive and nuisance pest and pathogen removal	—	✓	—	—	—	—	—	—
Invasive and nuisance plant species removal	—	—	✓	✓	—	—	—	—
Invasive and nuisance wildlife removal	—	—	—	—	—	—	—	—
Living shoreline creation	✓	—	—	—	✓	—	✓	—
Mangrove restoration	✓	✓	—	—	✓	—	—	—
Nontidal wetland restoration	✓	✓	✓	✓	—	✓	—	—

Table B.2 NBS strategies by expected implementation benefits and outcomes related to climate threat reduction *(continued)*

NBS Strategy	Reduced Flooding	Carbon Storage and Sequestration	Reduced Wildfire Risk	Drought Mitigation	Sea Level Rise Adaptation and Resilience	Heat Mitigation	Storm Protection	Improved Air Quality
Oyster bed restoration	✓	—	—	—	✓	—	✓	—
Peatland restoration	✓	✓	✓	✓	—	✓	—	—
Prescribed burns	—	—	✓	—	—	—	—	✓
Riparian buffer restoration	✓	✓	—	✓	—	✓	—	—
Riverine connectivity	✓	✓	—	✓	✓	—	—	—
Sagebrush conservation and restoration	—	✓	✓	—	—	—	—	—
Seagrass restoration	✓	✓	—	—	✓	—	✓	—
Stream restoration	✓	✓	✓	✓	—	✓	—	—
Thinning	—	✓	✓	✓	—	—	—	✓
Urban greening	✓	✓	—	—	—	✓	—	✓
Urban stormwater and runoff management	✓	✓	—	✓	—	✓	—	—
Wildlife road crossing structures	—	—	—	—	—	—	—	—

See strategy summaries for more information on how each project type creates these outcomes.

Table B.3 NBS strategies by likely ecological benefits and outcomes

NBS Strategy	Enhanced Biodiversity	Supports Wildlife	Improves Water Quality	Increases Primary Productivity	Invasive and Nuisance Species Management	Increases Habitat Connectivity	Supports Native Plants	Enhances Genetic Diversity	Enhances Soil Health	Reduces Runoff
Assisted marsh migration	✓	—	✓	✓	—	—	—	—	—	—
Beach nourishment	✓	✓	—	—	—	—	—	—	—	—
Beaver management and beaver analogs	✓	✓	✓	✓	—	—	—	—	—	—
Built wetlands	—	✓	✓	—	—	—	—	—	—	—
Coastal marsh restoration	—	✓	✓	✓	—	—	—	—	—	—
Coral reef restoration	✓	✓	✓	✓	—	—	—	—	—	—
Dune restoration	✓	—	—	✓	—	—	—	—	—	✓
Floodplain reconnection	✓	✓	✓	—	—	✓	—	—	—	—
Forest conservation and restoration	✓	✓	✓	—	✓	—	✓	—	—	—
Grassland conservation and restoration	✓	✓	—	—	—	—	—	—	✓	—
Green firebreaks	✓	—	—	—	—	—	—	—	—	—
Invasive and nuisance pest and pathogen removal	✓	—	—	—	—	—	—	—	—	—
Invasive and nuisance plant species removal	✓	✓	—	—	—	—	—	—	—	—
Invasive and nuisance wildlife removal	✓	—	—	—	—	—	—	—	—	—
Living shoreline creation	✓	—	✓	—	✓	—	—	—	—	—
Mangrove restoration	✓	✓	—	—	—	—	—	—	—	—
Nontidal wetland restoration	✓	✓	✓	✓	—	—	—	—	—	—

Table B.3 NBS strategies by likely ecological benefits and outcomes *(continued)*

NBS Strategy	Enhanced Biodiversity	Supports Wildlife	Improves Water Quality	Increases Primary Productivity	Invasive and Nuisance Species Management	Increases Habitat Connectivity	Supports Native Plants	Enhances Genetic Diversity	Enhances Soil Health	Reduces Runoff
Oyster bed restoration	✓	✓	✓	—	—	—	—	—	—	—
Peatland restoration	✓	—	✓	—	—	—	—	—	—	✓
Prescribed burns	—	✓	✓	—	✓	—	✓	—	✓	—
Riparian buffer restoration	✓	✓	✓	—	—	✓	—	—	—	—
Riverine connectivity	✓	✓	✓	✓	—	—	—	✓	—	—
Sagebrush conservation and restoration	—	✓	—	—	✓	—	✓	—	—	—
Seagrass restoration	✓	—	✓	✓	—	—	—	—	—	—
Stream restoration	✓	✓	✓	—	—	—	—	✓	—	—
Thinning	—	—	—	—	✓	—	✓	—	—	—
Urban greening	✓	✓	—	—	—	—	—	—	—	✓
Urban stormwater and runoff management	—	✓	✓	—	—	—	✓	—	—	✓
Wildlife road crossing structures	—	✓	—	—	—	✓	—	—	—	—

See strategy summaries for more information on how each project type creates these outcomes.

Table B.4 NBS strategies by likely social and economic benefits and outcomes

NBS Strategy	Jobs	Mental Health and Well-Being	Cultural Values	Recreational Opportunities	Reduced Erosion	Resilient Fisheries	Property and Infrastructure Protection	Food Security	Tourism	Increased Property Values	Agriculture and Timber Yields	Reduced or Avoided Costs	Aesthetics	Scientific Research	Aquifer Recharge	Clean Drinking Water	Firefighter Safety	Public Health and Safety	Limit Sprawl	Crime Reduction	Wind and Noise Reduction	Reduced Energy Use
Assisted marsh migration	✓	✓	✓	—	—	✓	✓	✓	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Beach nourishment	✓	✓	✓	—	✓	—	—	—	✓	✓	—	✓	—	—	—	—	—	—	—	—	—	—
Beaver management and beaver analogs	✓	✓	✓	✓	✓	✓	—	—	✓	—	—	—	—	—	✓	—	—	—	—	—	—	—
Built wetlands	—	—	—	✓	—	—	—	—	—	—	—	—	✓	—	—	—	—	—	—	—	—	—
Coastal marsh restoration	✓	✓	✓	✓	—	✓	✓	—	—	✓	—	—	—	—	—	—	—	—	—	—	—	—
Coral reef restoration	✓	✓	✓	✓	✓	✓	✓	✓	✓	—	—	—	—	✓	—	—	—	—	—	—	—	—
Dune restoration	✓	✓	✓	—	✓	—	✓	—	—	✓	—	✓	—	—	—	—	—	—	—	—	—	—
Floodplain reconnection	✓	✓	✓	✓	✓	✓	✓	—	—	✓	✓	—	—	—	—	—	—	—	—	—	—	—
Forest conservation and restoration	✓	✓	✓	✓	✓	—	—	—	—	—	✓	—	—	—	—	—	—	—	—	—	—	—
Grassland conservation and restoration	—	—	✓	✓	✓	—	—	—	—	—	✓	—	—	—	—	—	—	—	—	—	—	—
Green firebreaks	—	—	—	—	✓	—	✓	—	—	—	—	✓	—	—	—	—	✓	—	—	—	—	—

Table B.4 NBS strategies by likely social and economic benefits and outcomes *(continued)*

NBS Strategy	Jobs	Mental Health and Well-Being	Cultural Values	Recreational Opportunities	Reduced Erosion	Resilient Fisheries	Property and Infrastructure Protection	Food Security	Tourism	Increased Property Values	Agriculture and Timber Yields	Reduced or Avoided Costs	Aesthetics	Scientific Research	Aquifer Recharge	Clean Drinking Water	Firefighter Safety	Public Health and Safety	Limit Sprawl	Crime Reduction	Wind and Noise Reduction	Reduced Energy Use
Invasive and nuisance pest and pathogen removal	✓	—	—	—	—	—	—	✓	—	—	✓	—	✓	—	—	—	—	—	—	—	—	—
Invasive and nuisance plant species removal	—	—	—	—	—	—	—	✓	—	—	✓	—	—	—	—	—	—	—	—	—	—	—
Invasive and nuisance wildlife removal	✓	—	—	✓	—	—	—	✓	—	—	—	✓	—	—	—	—	—	✓	—	—	—	—
Living shoreline creation	✓	✓	✓	✓	✓	✓	✓	✓	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Mangrove restoration	—	—	✓	✓	—	✓	✓	✓	✓	—	—	—	—	✓	—	—	—	—	—	—	—	—
Nontidal wetland restoration	✓	✓	✓	✓	✓	—	—	—	—	—	—	—	—	✓	✓	—	—	—	—	—	—	—
Oyster bed restoration	✓	✓	✓	—	✓	✓	✓	✓	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Peatland restoration	✓	✓	✓	✓	✓	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Prescribed burns	✓	—	—	—	—	—	✓	—	—	—	—	—	—	—	—	—	✓	✓	—	—	—	—
Riparian buffer restoration	✓	✓	✓	—	✓	✓	—	—	—	✓	✓	—	—	—	—	—	—	—	—	—	—	—

Table B.4 NBS strategies by likely social and economic benefits and outcomes *(continued)*

NBS Strategy	Jobs	Mental Health and Well-Being	Cultural Values	Recreational Opportunities	Reduced Erosion	Resilient Fisheries	Property and Infrastructure Protection	Food Security	Tourism	Increased Property Values	Agriculture and Timber Yields	Reduced or Avoided Costs	Aesthetics	Scientific Research	Aquifer Recharge	Clean Drinking Water	Firefighter Safety	Public Health and Safety	Limit Sprawl	Crime Reduction	Wind and Noise Reduction	Reduced Energy Use
Riverine connectivity	✓	✓	✓	✓	—	✓	—	—	—	✓	—	—	—	—	—	✓	—	—	—	—	—	—
Sagebrush conservation and restoration	✓	—	✓	✓	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Seagrass restoration	✓	✓	✓	✓	✓	✓	—	—	—	—	—	—	—	—	—	—	—	✓	—	—	—	—
Stream restoration	✓	✓	✓	✓	✓	✓	—	—	—	—	—	—	—	—	—	✓	—	—	—	—	—	—
Thinning	✓	—	—	—	—	—	✓	—	—	—	✓	—	—	—	—	—	—	—	—	—	—	—
Urban greening	✓	✓	—	✓	—	—	—	—	—	—	—	—	✓	—	—	—	—	—	—	✓	✓	—
Urban stormwater and runoff management	—	—	—	✓	✓	—	—	—	—	✓	—	—	✓	—	✓	—	—	—	—	—	—	✓
Wildlife road crossing structures	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	✓	—	—	—	—

See strategy summaries for more information on how each project type creates these outcomes.

Coastal Habitats
1. Assisted Marsh Migration

DEFINITION

Assisted marsh migration is a strategy of marsh conservation that works with the inland movement of coastal marshes as a response to rising sea levels. Within a marsh, the plants closer to the coastline are more frequently inundated with water and are thus more salt tolerant (Vanderveer 2023). However, sea level rise has resulted in both high and low tides moving further up the shoreline, flooding a greater percentage of the marsh. In response to this, marsh plants begin to naturally move into upland zones, seeking conditions that best match their desired salinity and water exposure (LCCN n.d.). Barriers such as seawalls, roads, canals, and homes can prevent marsh from migrating inland, resulting in loss of marsh habitat with sea level rise. Assisted marsh migration often consists of creating marsh migration corridors, moving infrastructure, removing invasive species, transplanting plants, and digging runnels (Bergeson 2023, Vanderveer 2023).

TECHNICAL APPROACH

Assisted marsh migration consists primarily of three components: (1) removing or preventing upland obstacles, (2) enhancing upland topography and hydrology, and (3) facilitating the movement of marsh plants. Many assisted marsh migration projects do not contain all three components because of the land uses around the site (Bergeson 2023). Assisted marsh migration projects are often part of a larger resist-adapt-direct ecosystem management framework. Once land managers can no longer resist the inevitable decline of a marsh ecosystem resulting from sea level rise, they must adapt management strategies accordingly. Directing naturally occurring movement of coastal marsh ecosystems in a coherent manner is the final step of this process (Schuurman et al. 2020). This can take the following forms:

1. **Removing or preventing upland obstacles:** Once an area has been developed, it is very difficult to convince people to move out (Lipuma 2021). Thus, marsh migration corridors must be planned preemptively before significant development occurs in the region. Conservation easements and buyout programs are two of the most common ways of acquiring land (Field et al. 2017).

    - **Moving infrastructure:** It is very difficult to displace urban development for a marsh migration corridor. However, individual roads and outlying flood control infrastructure can sometimes be moved. As sea level rises, rural communities may move and flood control infrastructure may no longer be necessary (Enwright et al. 2016). Additionally, saltwater intrusion into nearby agricultural areas reduces yields and may make farming in many areas economically infeasible. Clearing old farm equipment is necessary before converting agricultural areas into marshes (Tully et al. 2019).

- **Removing invasive species:** Invasive species are common in the underbrush of forests in the path of marsh migration. While most native trees may die naturally, hardier invasive shrubs generally persist longer. These species will need to be removed as well as the common reed (*Phragmites australis*). While *Phragmites australis* can aid marsh migration due to its greater tolerance for brackish water, it can disrupt the growth of native marsh plants in the long term (Smith 2013).

2. **Enhancing upland topography and hydrology:** Many coastal areas have been diked and drained to accommodate farming in low-lying areas. This hydrology must be reversed to let water into the migration corridor (Anisfeld et al. 2016).

    - **Digging runnels:** As high tides penetrate further inland, large amounts of water often get trapped in upland areas as the tide recedes. These high levels of inundation cause marsh vegetation to drown. To solve this problem, shallow channels called *runnels* are dug to help drain the water (Figure 1). This restores the natural marsh hydrology and allows for the vegetation to grow back (Vanderveer 2023).

Figure 1.1 Digging ditches to improve drainage and remove invasive plants in Sachuest Point National Wildlife Refuge

Photo courtesy US Fish and Wildlife Service

- **Dike removal:** Dikes were built to convert former marshes into farmland or other human development. As sea levels rise, many of these areas are no longer as productive. Dikes must be removed to restore natural tidal exchanges, allowing frequent inundation to support marsh plants. Tides also bring in enough salt water to support halophyte marsh plants (Smith et al. 2009).
- **Microtopographic alterations:** Topography is one of the main factors limiting marsh migration. Marshes can only move to areas with a slightly higher elevation and cannot climb up steep slopes (Molino et al. 2022). To make upland areas more accessible for marsh migration, any high gradients must be lowered. This allows for tidal water to enter the area unimpeded.
- **Grass bundle staking:** Many tidal exchanges come into upland areas too fast, limiting the deposition of sediment that drives the natural accretion process. This is critical to help marshes keep adding elevation at the same pace as sea level rise. Grass bundle staking involves rolling cut grass into bundles and staking them in upland areas. The bundles help slow the tides and capture sediment (DU 2012).
- **Filling ditches with dredged material:** Many ditches have been created in marsh migration corridors to control mosquito populations or enhance agricultural productivity. These ditches lower the water table, making areas inhospitable to marsh species (Nolan 2018). To fill these ditches, or any other upland area that is frequently inundated with water, layers of dredged material are often used. Large amounts of dredged material are already being produced to deepen coastal waterways, making assisted marsh migration projects a great beneficial use of dredged material (Weinstein and Weishar 2002).

3. **Facilitating the movement of marsh plants:** As coastal conditions change, marsh plants will naturally begin to migrate inland. However, this movement is contingent upon there being the appropriate space, salinity, topography, and hydrology to support marsh plants (Linhoss et al. 2015). While it is rare to see marsh migration projects moving plants inland, there are several ways to facilitate movement into marsh migration corridors.

   - **Cutting marsh grass:** Mowing marsh grass and placing the cuttings further inland helps direct marsh migration. Seeds from stems in the cuttings will colonize the upland habitat (DU 2012).
   - **Transplanting endangered species:** While most species can migrate on their own to upland habitats, endangered species already on the decline may not have the ability to do so. The Endangered Species Act lists many species that reside in marshes threatened by sea level rise, including the Cape Sable thoroughwort (*Chromolaena frustrata*) and aboriginal prickly-apple (*Harrisia aboriginum*). Endangered species should be transplanted to ensure their survival (Lopez 2015).
   - **Seeding:** Distributing seeds across upland fields in marsh migration corridors infuses genetic diversity into marsh communities when sexual reproduction occurs. Seeding jump-starts the succession process of old agricultural fields, preventing a *Phragmites australis* invasion before the native marsh plants arrive (Gedan and Fernández-Pascual 2019).

OPERATIONS AND MAINTENANCE

Similar to restored coastal marshes, maintenance needs are likely to include periodic invasive species removal and may require occasional replanting with native species.

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Old agricultural fields:** While marsh communities in old agricultural fields tend to have a greater composition of shrubs than traditional marshes, they are better able to repel invasive species. Furthermore, agricultural fields are in early stages of succession and devoid of canopy cover that limits light necessary for marsh plants to grow. Agricultural fields also provide fewer ecosystem services than terrestrial forests, limiting the trade-offs that occur when they are replaced by coastal marshes (Gedan and Fernández-Pascual 2019).
- ✓ **Lawns:** Similar to old agricultural fields, lawns lack canopy that stymies growth and provide virtually no ecosystem services. Unlike upland forests, lawns do not have leaf litter that discourages marsh plant growth (Anisfeld et al. 2016).
- ✓ **Tidal inundation frequency of 0.5% to 20% of high tides:** Inundation is the driver of plant movement. As the tides creep up the shore, both upland and marsh plants track this movement to be aligned with their ideal salinity and inundation conditions. Areas with current tidal flooding frequencies between 0.5% and 20% are good candidates for marsh migration. This range captures areas that receive enough tidal exposure to support halophytes but still accounts for future sea level rise (Anisfeld et al. 2016).
- ✓ **Areas with slopes less than 1%:** Marshes need extremely flat topography to migrate inland because of their need for hydric soil and inundation from tidal exchanges (Smith 2020).
- ✓ **Salinity levels of 5 to 30 ppt:** Halophytes need a baseline level of salt to survive and compete against established upland plants (VDCR 2021).
- ✗ **Hazardous and contaminated sites:** In many urbanized areas, brownfield sites often abut coastal marshes. If a marsh migrates into one of these sites, then the inundation of the soil has the potential to release toxic chemicals in the water (Burman et al. 2023).
- ✗ **Urbanized areas:** *Coastal squeeze* refers to the convergence of urban development and sea level rise compressing intertidal habitats from both sides. Urban areas are not ideal marsh migration corridors because of the prevalence of impervious surfaces and contaminated runoff (Enwright et al. 2016).
- ✗ **Diked areas that won't be removed as a part of the project:** Dikes alter tidal flow, limiting the amount of salt water that reaches the area. Diked areas generally do not have enough water to support marsh plants (Wasson et al. 2013).
- ✗ **Far away from current marshes:** Marshes do not tend to migrate long distances and usually are displaced to the habitat directly upland of their original location.

- **Lack of connectivity:** If anthropogenic barriers lie in between the marsh migration corridor and the current location of the marsh, the area is not suitable for marsh migration. Levees, urban development, and dikes are all barriers that threaten to disconnect marsh migration corridors (Clough 2013).

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?
Sea Level Affecting Marshes Model (SLAMM)	Online model	Created in the 1980s, updated every year	National Oceanic and Atmospheric Administration (NOAA), Warren Pinnacle Consulting	National	Part of NOAA's Digital Coast toolbox, SLAMM helps predict where marshes will migrate to under threat from rising seas. The model contains helpful inputs including dike locations, accretion rates, and erosion rates. An explainer document is available.	✓	✓	—	—
Sea Level Rise Viewer	Online model	Updated in 2023	NOAA	National	To plan for future sea level rise, this tool allows viewers to visualize coastal flooding for up to 10 ft of sea level rise. The model also contains photo simulations of landmarks under certain sea level rise scenarios, projected marsh migration and socioeconomic vulnerability.	✓	✓	—	—
Marshes on the Move	Document	2011	NOAA, The Nature Conservancy (TNC)	National	This guide helps project managers make sense of the variety of marsh migration modelling software available. The authors discuss the pros and cons of using models as well as the factors the determine marsh migration.	✓	✓	—	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Managed Retreat Toolkit	Website	N/A	Georgetown Climate Center	National	Focusing on the policy tools needed to implement an assisted marsh migration project, this website helps weigh the social and ecological concerns related to marsh migration. Additional topics covered include regulatory considerations, infrastructure removal, and planning tools.	✓	—	—	—
A Guide to the Control and Management of Invasive *Phragmites*	Guidebook	2014	Michigan Department of Environment, Great Lakes and Energy	Designed for the Great Lakes region but most of the information is more broadly applicable	Covering all aspects of *Phragmites* control, this guide recommends a plethora of control and management strategies. Eliminating *Phragmites* and other invasive species is a major challenge for assisted marsh migration projects.	✓	—	✓	—
Conservation Reserve Enhancement Program	Fact sheet	2021	US Department of Agriculture	National	The Conservation Reserve Enhancement Program is one of the main mechanisms by which project managers can acquire farmland suffering from saltwater intrusion for assisted marsh migration projects. This document highlights the benefits of using this program for both farmers and the environment.	✓	—	—	—
Coastal Wetlands and Sea Level Rise: A Path to Climate Change Adaptation	Document	2015	Massachusetts Office of Coastal Zone Management	Designed for New England but most of the information is more broadly applicable	The report focuses on translating marsh migration model results into implementing a successful project. Additional topics covered include monitoring, case studies, and overcoming barriers to marsh migration.	✓	—	✓	✓

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Wetland Monitoring Guidelines	Guidebook	1999	US Fish and Wildlife Service (USFWS)	National	This guide covers all aspects of monitoring protocols for wetlands, including baseline data requirements and qualities to monitor for. The authors also discuss how to align monitoring operations with the goals of the project.	—	✓	✓	—
Use of Thin Layer Placement of Dredged Material for Salt Marsh Restoration	Guidebook	2017	Georgia Coastal Research Council, University of Georgia	National	Thin layer placement is a tool used in many restoration projects to replace natural accretion processes or make microtopographic alterations. Additional topics covered include case studies, monitoring, site suitability and site surveys.	✓	✓	✓	✓

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Sea level rise adaptation and resilience:** While sea level rise is the driver of marsh migration, an intact marsh further upland is more resilient to future increases in sea level rise than a drowning marsh in its original location. Marshes that have undergone migration are better equipped to trap sediment, increasing accretion rates to generate elevation gains (Raposa et al. 2016).

- **Reduced flooding:** Marshes are a vital buffer zone protecting urban and agricultural areas from storm surges. However, with sea level rise, the area occupied by the marsh is decreasing, reducing its ability to protect against catastrophic flooding. Assisted marsh migration preserves the storm protection capabilities of marshes by allowing them to grow. This protects the areas behind the marsh from property damage and saltwater intrusion (Guimond and Michael 2020).

- **Storm protection:** While marsh migration results in greater amounts of coastal inundation than an intact marsh, a marsh that has moved upland still retains many of the same protective qualities. Protecting marsh migration corridors keeps vital infrastructure out of harm's way during severe storms (Bigalbal et al. 2018). Preserving the marsh area helps protect its storm attenuation abilities (Narayan et al. 2017).

Social and Economic

- **Property and infrastructure protection:** Marshes that moved upland still provide the same protection against high wave energy and storm surges. This protects properties behind the marsh from the impacts of severe storms (Kirwan et al. 2016).
- **Resilient fisheries:** Marshes serve as nurseries and habitats for a plethora of fish species. This results in an increase in both finfish and shellfish harvests in the surrounding waterbodies (Olander et. al. 2021).
- **Food security:** Some rural residents rely on locally caught seafood as their primary source of nutrition. Therefore, increases in fish harvests enhance food security (Olander et. al. 2021).
- **Jobs:** Contractors will need to be hired to perform restoration activities, investing in the local economy.
- **Mental health and well-being:** Preserving marsh habitat enhances residents' access to greenspace, boosting mental health and psychological well-being.
- **Cultural values:** Assisted marsh migration protects the marsh ecosystem for future generations, increasing awareness and appreciation of this special ecosystem.

Ecological

- **Improved water quality:** Marshes trap and absorb sediment, nutrients, and chemical pollutants such as heavy metals and hydrocarbons, preventing them from entering nearby waterways (Craft 2001, Padial and Thomaz 2008, Mason et al. 2018).
- **Increase in primary productivity:** In marshes, light availability is generally the limiting factor of phytoplankton abundance. As more light can reach the phytoplankton, their biomass increases, supporting the entire food web (Cole and Cloern 1987).
- **Enhanced biodiversity:** Birds, fish and invertebrates all rely on marshes for parts of their life cycles. Marshes are vital nursery grounds for many fish and multiple bird species use marshes as their primary habitat. A growth in marsh area increases biodiversity through all trophic levels (French McCay and Rowe 2003).

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 assisted marsh migration are included here.

- **Expense:** For projects that use dredged material to alter topography, transporting this heavy material over long distances can be quite costly. However, if there is already planned dredging activity nearby, then this material can be used in assisted marsh migration, reducing these costs (TNC 2023).
- **Capacity**
- **Public opinion**
- **Conflict with other land uses:** Marsh migration is frequently seen as a threat to agriculture because of the amount of agricultural land it replaces. Agricultural land is generally flat and lacks thick canopy cover, making it ideal for marsh migration. Marsh migration has already overtaken significant amounts of farmland in many coastal counties (Gedan et al. 2020). Despite this, farmers can still use their land to create additional revenue streams in the wake of decreasing yields. Farmers have shown willingness to profit from hunting, birding, and conservation programs on their properties (Sudol et al. 2023). Coastal squeeze, where marshes are trapped between encroaching development and rising seas, is also a major threat to marsh migration. Developers often resist marsh migration and attempt to protect land by armoring the shoreline or adding additional substrate to raise their property. Properties in marsh migration corridors are often expensive because of their proximity to the coast (Mills et al. 2015).
- **Regulation**
- **Lack of effectiveness data**

Community

- **Declining property values:** Marsh migration has been shown to depress surrounding property values. It is difficult to control where marsh plants migrate because of local topographic and hydrological regimes. Marsh plants will often independently migrate to lawns of residences further inland, creating a soggy and potentially structurally unsound structure (Van Dolah et al. 2020). However, this impact is inevitable with rising seas, regardless of whether an assisted marsh migration program is undertaken.
- **Displacement of local communities:** The spillover effects of marsh migration, including more frequent tidal inundation, may cause some residents living near marsh migration areas to leave (Van Dolah et al. 2020). Some amount of community displacement in response to sea level rise is likely inevitable whether or not assisted marsh migration occurs.

- **Infrastructure loss:** Rising water tables associated with marsh migration may compromise the structural integrity of nearby roads. Many roads are often maintained by a different entity than the one leading the migration project, a source of potential conflict (GCC n.d.).

Ecological

- **Loss of carbon sequestration:** Although coastal wetlands are large carbon sinks, the conversion of upland forests to marshes can result in net carbon emissions. The loss of the original marsh closer to the coast as well as the millions of tons of carbon emissions from dying forests further upland can make marsh migration a carbon source (Warnell et al. 2022).
- **Loss of upland forest habitat:** As saltwater intrudes into upland forest ecosystems and freshwater wetlands, these ecosystems experience a rapid die-off. Termed *ghost forests*, degraded upland forests emit large amounts of carbon and become scarcer with sea level rise. Complex trade-offs are involved when weighing the benefits of these forests versus marshes (Kirwan and Gedan 2019).
- **Invasive species:** *Phragmites australis,* a widespread invasive species, is primarily located at the upper boundary of marshes, meaning that it is the first colonizer in marsh migration. While thought to only grow in high light areas, *Phragmites australis* has been shown to grow in areas with dense canopy cover. The result is that when the native marsh plants migrate, the new site has already been invaded by *Phragmites australis* (Shaw et al. 2022).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Blackwater National Wildlife Refuge Marsh Migration	Blackwater National Wildlife Refuge, MD	**USFWS,** TNC, US Army Corps of Engineers (USACE)	Sediment dredging, invasive species removal, cutting down dead or dying trees, planting transitional crops	870	Not provided	7 years	TNC has helped USFWS acquire more land to create marsh migration projects within the corridor. Many strategies are being used, including dredging sediment, removing *Phragmites* and nutrias, cutting down trees, and planting transitional crops in agricultural areas.	Sea level rise, coastal flooding	Local farmers were involved in the restoration activities to help gain their support for the project.
Ocean View Farms Marsh Migration Project	Dartmouth, MA	Dartmouth National Resources Trust, US Environmental Protection Agency, Southeast New England Program	Invasive species removal, digging runnels, seeding	125	Not provided	4 months	Workers removed invasive species, seeded salt marsh plants, and dug runnels to help water escape from impounded areas inland.	Sea level rise, coastal flooding, increased storm severity	Additional cobenefits of the project are reduced rates of erosion and natural mosquito control.
Narrow River Restoration Project	John H. Chafee National Wildlife Refuge, RI	**USFWS,** TNC, USACE	Dredged material placement, planting native marsh plants	14	Not provided	3 months	After this marsh was devastated by Hurricane Sandy, a thin layer of dredged material was placed to revive the marsh. This will give the marsh the opportunity to migrate landward in the future.	Sea level rise, coastal flooding, increased storm severity	Dredged material was placed on the site using a bulldozer that used computer-aided design to place the sediment in ideal locations.

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Community Science Salt Marsh Restoration and Monitoring Project	Charleston County, SC	South Carolina Sea Grant Consortium, NOAA, SC Department of Natural Resources, Clemson Cooperative Extension	Collecting and planting *Spartina alterniflora* seedlings	Not provided	Not provided	4 years	Volunteers collected seeds of *Spartina alterniflora*, which were then grown in a greenhouse. The seedlings were then planted in locations further inland.	Sea level rise	Volunteers also helped with monitoring efforts using the Anecdata app.
Island Road Marsh Creation and Nourishment	Isle de Jeane Charles, LA	NOAA, **US Geological Survey,** Louisiana Coastal Protection and Restoration Authority	Placement of a layer of sediment, creating gaps in a dike	295	34.3 million	Ongoing	In an area experiencing severe land loss, workers will create gaps in a dike and placement of a layer of sediment to promote marsh growth. The project will consolidate the remaining marsh in the area to protect the only hurricane evacuation route for the Isle de Jeane Charles community.	Sea level rise, coastal flooding, increased storm severity	Not provided

Bolding indicates DOI affiliates.

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Coastal Habitats
2. Beach Nourishment

DEFINITION

Beach nourishment is the addition of sediment, usually sand, directly on or adjacent to an eroding beach (USACE n.d.a). Beach nourishment involves transporting large quantities of sand to the eroding beach to help stabilize it. The additional sand is then redistributed across the intertidal zone by natural processes such as incoming wave energy and managed erosion (USACE 2007). Sand can either be transported overland from inland sources or dredged from nearby areas offshore. Beach nourishment falls under the category of *soft* or *green* shoreline defenses because, while significant human alterations to the shoreline are involved, beach nourishment uses natural processes of sediment deposition, whereas gray infrastructure does not. Beach nourishment is increasingly necessary as natural sediment deposition processes are disrupted by anthropogenic activities like urban development, damming rivers, and dredging channels (Staudt et al. 2021). The impacts of climate change, especially sea level rise and increased storm severity, require more frequent beach nourishment (Stive et al. 1991).

TECHNICAL APPROACH

Implementing a beach nourishment project requires moving large amounts of sand into the correct position on the beach. The process varies considerably depending on the source of the sand (Haney et. al. 2007). When choosing which source to use, managers must consider the compatibility of the new sand with naturally occurring sand at the beach. Sand sources must have similar composition, texture, and color to natural sand in order for the project to be successful (Parkinson and Ogurcak 2018). There are several sand source options:

- **Sand from offshore sources:** Dredging sand directly offshore from the recipient beach is the most common technique of beach nourishment (Figure 1). A hopper or pipeline dredge sucks sediment up from the bottom of the ocean and then pumps it onto the beach via a long tube (NPS 2019). While this method reduces the logistical complexities of transporting sand, it can have detrimental impacts on bottom-dwelling and migratory species (NRC 1995).
- **Sand from inlet sources:** The dredging process is similar to extracting sand from offshore sources, except that the dredge is usually smaller. Sand from a nearby inlet, sound, or waterway is dredged onto the beach. The advantage of this approach is that the sediment source is more frequently replenished from depositions of inland rivers (Qiu et al. 2020).
- **Sand from upland sources:** Retrieving sand from upland sources and transporting it to the beach has been an increasingly popular method of beach nourishment because of lower mobilization costs and greater quality control. Inland sand mines harvest the

sand, which is then loaded on trucks that transport it to the beach. The downsides of this approach are that it takes thousands of truckloads to complete large projects and the trucks need access to the beach (Brenner 2016).

- **Sand from previously planned dredging projects:** Sediment is frequently dredged for other purposes besides beach nourishment, usually to deepen shipping channels around commercial ports. Using the sediment gathered during these projects for beach nourishment helps limit the cost of dredging sand. It also lessens the environmental impact of dredging and reduces the amount of dredged material that ends up in landfills (USACE n.d.b).

Sometimes, sand is not placed on the subaerial (above water) portion of the beach because of ecological or financial constraints (NPS n.d.). Alternative strategies involve depositing the sediment closer to the dredge site, reducing transportation costs. These techniques rely on natural currents to transport the sediment to the target beach (Dean 2002). Ecologically, these techniques are often selected because benthic communities further offshore can recover more quickly after nourishment than those in the intertidal zone (Essink et. al. 1997). Therefore, the following alternative beach nourishment strategies are often used:

- **Subaqueous nourishment:** *Subaqueous nourishment* involves dredging sediment and depositing it offshore of the beach in berms. Over time, wave action will help the sand migrate shoreward and gradually replenish the beach (Atkinson and Baldock 2020).

Figure 2.1 Nourishment of Ocean View Beach in Virginia via dredging and sand redistribution

Photo courtesy US Army Corps of Engineers

- **Sediment bypassing:** *Sediment bypassing* is where the dredged material is dumped downdrift of the desired nourishment location. Sediment bypassing is often paired with the dredging of an armored inlet, replacing the lost source of sediment associated with hard armoring (NPS n.d.). The sediment is then carried by the current to the desired location (Dean 2002).

Small Island Creation

Small island creation is a particular type of beach nourishment where a previously submerged island is rebuilt via dredged sediment. The process of small island creation is similar to both beach nourishment and thin layer placement in coastal marsh restoration. However, a major difference is that the recipient area has already been submerged, complicating the process of depositing dredged sediment at the site (USACE n.d.a.).

Small island creation is primarily used to create barrier islands or restore salt marshes that have previously been submerged. Barrier islands have many benefits, including storm protection and recreational value (Morton 2008). Barrier islands are naturally ephemeral geomorphic features, with inlet formation and sediment transport constantly changing. However, hardened shorelines have hastened the decline of sediment transport, resulting in the need for island nourishment and small island creation (Feagin et al. 2010).

In the context of salt marshes, small island creation is viewed as alternative to assisted marsh migration. Within the resist-adapt-direct framework of ecosystem management, assisted marsh migration would be under the *direct* phase while small island creation would be considered *resisting* (Schuurman et al. 2020). Small island creation is used in scenarios where the upland habitat is not suitable for marsh migration, but managers still want to preserve it. Small islands are created within the inundated marsh using dredged material. Marsh vegetation will then migrate to or be planted on the island, preventing the marsh from being submerged (Myszewski and Alber 2017).

The sustainability of small island creation projects has often been questioned because of the rapid pace of sea level rise. Even if the island can remain above sea level for a few more years, subsequent nourishment events will be needed to combat tidal erosion. Modeling sea level rise at the site is important to understand the longevity of the project's benefits (Stive et al. 1991).

OPERATIONS AND MAINTENANCE

After beach nourishment, it is necessary to plow the sand to prevent compaction. Beach access points must also be maintained as sand shifts following nourishment. Because beach nourishment does not address the cause of sand erosion that threatens beaches, it must be repeated every 2 to 10 years to maintain the beach width (Staudt et al. 2021).

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Gently sloping beaches with minor upland erosion:** Steep cliffs and severe erosion make it difficult to complete beach nourishment (VIMS 2023).

- ✓ **Proximity to already-planned channel dredging projects:** Beneficial use of dredged material agreements are much easier to facilitate when the dredging location is close to the beach nourishment project. Dredged sediment is very heavy and difficult to transport (VIMS 2023).
- ✓ **Established groin fields with sand present:** Adding onto an already existing beach is much easier than recreating a beach after all the sand has already eroded (VIMS 2023).
- ✓ **Beach that receives significant recreational use:** Recreation is one of the major drivers of beach nourishment. Beach nourishment widens the beach, increasing its ability to handle more beachgoers.
- ✓ **Upland infrastructure at risk of flooding directly behind the beach:** Beach nourishment provides additional space between the ocean and development, protecting property from sea level rise and storm surges (TGLO n.d).
- ✗ **Presence of submerged aquatic vegetation or mangroves:** Beach nourishment can significantly degrade these ecosystems, reducing their coastal protection capacity (Nunez et al. 2022).
- ✗ **Special geomorphic features, such as sand spits:** Sand spits and other special geomorphic features are highly ephemeral. It is not worth investing in beach nourishment for an area that will naturally disappear (Nunez et al. 2022).
- ✗ **Area where sand migration will inhibit boat navigation or surrounding land uses:** In small waterways, beach nourishment will take over a significant portion of the channel with sand. This will compromise the navigability of the waterway (VIMS 2023).
- ✗ **Bank height greater than 9 meters:** Erosion on banks greater than 9 m is generally not caused by tidal erosion, which beach nourishment is meant to address. Beach nourishment is unable to mitigate other drivers of erosion such as overland runoff, upland development, and vegetation management (Nunez et al. 2022).
- ✗ **Directly in front of a seawall:** Seawalls are drivers of erosion. Investing in beach nourishment in areas that are experiencing accelerated erosion from anthropogenic factors is not a viable strategy (Thibodaux 2018).

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?
Handbook of Coastal Processes and Erosion, Chapter 11: Principles of Beach Nourishment	Book chapter	2017	Paul D. Iomar	National	This guide gives a framework for designing beach nourishment projects and weighing the trade-offs between different sediment sources. Other topics include estimating the life expectancy and slope adjustment for a project.	✓	—	—	✓
Beach Nourishment: Theory and Practice	Guidebook	2002	World Scientific	National	Developed to be used by project designers, this book contains information relating to designing and executing a successful beach nourishment project. Accounting for differences in sediment sizes, bathymetry, and beach profiles are all covered.	✓	—	—	✓
Beach Nourishment Resiliency Design Guide	Guidebook	n.d.	Texas Government Lands Office	Designed for Texas but most of the information is more broadly applicable	This easy-to-read guide covers all the main elements of beach nourishment, from analyzing the site characteristics to monitoring. Included is a helpful infographic that lays out the entire spectrum of green to gray shoreline defense techniques.	✓	—	✓	—
State, Territory and Commonwealth Beach Nourishment Programs	Guidebook	2000	National Oceanic and Atmospheric Administration (NOAA)	National	NOAA provides an overview of the beach nourishment programs and projects across the United States. Additional topics covered include funding sources for projects, alternative strategies for managing beach erosion, and issues regarding beach nourishment.	—	—	—	✓

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Beach Nourishment and Protection	Guidebook	1995	National Research Council	National	This guide covers beach nourishment design, predicting future erosion, and the role of federal agencies in the process. The authors also outline the monitoring process and economic feasibility of projects.	✓	✓	✓	—
Beach Nourishment	Guidebook	2007	Massachusetts Department of Environmental Protection	Designed for Massachusetts but most of the information is more broadly applicable	Beach stability determinations, information about permit requirements, and monitoring plans are just some of the information presented in this practical guide. The authors provide a helpful six-step plan for beach nourishment and address the problem of getting source sediment to match the sediment of the receiving beach.	✓	✓	✓	—
Shoreline Protection Assessment: How Beach Nourishment Projects Work	Document	2007	USACE	National	The authors describe the value of beach nourishment projects as well as the engineering considerations that go into them. Additional topics covered include the environmental implications of beach nourishment and how projects respond to storms.	✓	—	—	✓
National Beach Nourishment Database	Database	2023	American Shore & Beach Preservation Association, APTIM	National	This resource is a compilation of every beach nourishment project in the United States. Equipped with a map to help navigate the projects, the database includes the cost of beach nourishment projects as well as how many nourishment events have been completed.	—	—	—	✓

GRAY INFRASTRUCTURE ALTERNATIVES

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

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Storm protection:** Beach nourishment is highly effective at reducing impacts from severe storms, averting millions in property damage. However, the storm may significantly degrade the beach itself, requiring another round of nourishment to extend the benefits into the future (Pompe and Rinehart 1995).
- **Reduced flooding:** Beach nourishment serves as a vital defense against storm surges. Waves must travel over longer distances of a nourished beach during a storm surge, resulting in communities with beach nourishment avoiding significant flood damage (Jones and Mangun 2001).
- **Sea level rise adaptation and resilience:** Beach nourishment has been shown to lessen the impacts of sea level rise. Beach nourishment provides a greater buffer zone in between the ocean and developments, allowing for the coastline to absorb rising sea levels. Nourishing the underwater portion of the shore is also important to allow the shore to accrete (Stive et al. 1991).

Social and Economic

- **Tourism:** Tourism is often the economic engine of coastal resort towns, with beach access being the primary draw for visitors. Therefore, preserving a wide and accessible beach is a paramount concern for many communities. Studies have shown that even expensive beach nourishment projects usually pay for themselves in tourism revenues (Jones and Mangun 2001).
- **Reduced or avoided costs:** Beach nourishment has reduced the cost of flood insurance in many properties surrounding the project (Leatherman 2018).
- **Increased property values:** Beach nourishment has been shown to increase the value of nearby properties. This results from the storm protection that wider beaches provide as well as the increase in recreational and tourism opportunities (Edwards and Gable 1991).
- **Cultural values:** Beaches are highly valued in American culture and are a vital source of recreation for millions of people each year (Wolch and Zhang 2017).

- **Mental health and well-being:** Beach nourishment helps restore public shorelines, boosting mental health and psychological well-being.
- **Jobs:** Contractors will need to be hired to operate the extensive machinery required for a beach nourishment project, contributing to the local economy.
- **Reduced erosion:** While coastal erosion has increased globally as sea level rise and severe storms degrade coastlines, areas with beach nourishment have had an increase in accretion of sediments as opposed to erosion. This has been seen along the Atlantic Coast of the United States, where there has been a long-term shift toward accretion resulting from the prevalence of beach nourishment (Armstrong and Lazarus 2019). While beach nourishment does not temper the drivers of erosion, it is still able to mask the effects. On the other hand, gray infrastructure such as seawalls accelerates erosion, significantly degrading intertidal habitat (Pilkey and Wright 1988).

Ecological

- **Supports wildlife:** Unlike gray infrastructure, which eliminates intertidal habitat, beach nourishment increases the amount of intertidal habitat available for use by wildlife species. While this habitat may be temporarily disrupted during nourishment events, it helps protect the ecosystem in the long term (Speybroeck et. al. 2006). Downdrift and upland habitats adjacent to beach nourishment projects reap the benefits of beach nourishment projects as well. Erosion of sediment from the beach to downdrift undeveloped habitats helps restore the role of developed areas as sediment sources. Beach nourishment also buffers upland dune and marsh habitats by dissipating most of the wave energy (Nordstrom 2005). Sea turtles are one species of high conservation value that benefit from beach nourishment. Beach nourishment helps increase sea turtle breeding grounds that have suffered from sand deficits as a result of hard armoring. While nourishment events can disrupt sea turtles' nests, these can be strategically timed to avoid conflicts (Montague 2008).
- **Increased biodiversity:** While beach nourishment can have deleterious effects on the ecosystem in the short run, the disruption caused by beach nourishment can create a greater diversity of habitats within the cycle of succession. Beach nourishment helps address the lack of early succession communities in coastal habitats, creating a diversity of habitats that favors a wide variety of species. Furthermore, beach nourishment protects coastal habitats against sea level rise and erosion, enhancing their long-term sustainability (Kindeberg et al. 2023).

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 beach nourishment are included here.

- **Expense:** Beach nourishment is expensive because of the large amount of equipment needed to complete a project. Mobilization costs for dredges alone range from $100,000 to over $1 million (TGLO n.d.). These high mobilization costs make transporting sand from upland mines more economical for smaller projects. However, for large projects, dredges make more sense as the large volume of sediment deposited pays for the high upfront cost (Dobkowski 1998). In recent years, the cost of beach nourishment has been rising, with the average increasing $10 per cubic meter. Beach nourishment projects are known to overrun cost estimates because of delays, storms, and logistical challenges (Parkinson and Ogurcak 2018).

- **Capacity**
- **Public opinion**
- **Conflict with other land uses**
- **Regulation**
- **Lack of effectiveness data**

Economic

- **Required repetition:** Beach nourishment is not a permanent fix to eroding shorelines and must be redone periodically to restore the beach. Facing the prospect that an investment of millions of dollars may only result in two years of protection makes beach nourishment infeasible for many communities (Smith et al. 2009).
- **Need for tourism to recoup the cost:** Most beach nourishment projects are undertaken by local municipalities who justify the high cost by pointing to increases in property values and tourism, both vital sources of tax revenue. However, projects on federal lands do not reap these same benefits because there is no private property to tax and most units do not charge entrance fees. Thus, it may be more difficult to secure funding for federal land managers than local municipalities (NRC 1995).

Community

- **Heavy truck traffic:** For projects that use upland sources of sediment, a large number of trucks will be needed to transport the sand to the nourishment site. Many coastal communities have limited highway access and the truck trips for the project may plunge the entire community into gridlock. Trucks used for the Sandy Hook beach nourishment project in New Jersey caused the destruction of beach dunes, snarled local roads, and closed the beach to recreational users (Nordstrom et al. 1978). Most trucks can only carry 12 to 18 y^3 of sediment (Smith 2013). For example, an average-sized beach nourishment project of 5,400 y^3 would require 360 truck trips (Cipriani et al. 1999)
- **Positive feedback loop of development:** Beach nourishment gives communities a greater sense of security despite the grave risks of sea level rise, erosion, and severe storms associated with living along the coast. After a beach nourishment event, more developments are built behind the nourished beach. While this may be advantageous to individual developers, increased urbanization along the coast lessens resiliency to climate change in the long term (Armstrong et al. 2016).

- **Temporary lack of beach access:** During a nourishment event, beaches must be temporarily closed to the public to ensure safety while the heavy equipment works on the beach. Beach nourishment must be performed under ideal weather conditions, which coincides with the main tourism season. Coastal communities may lose portions of a lucrative tourism season if the beach is closed (Smith 2013).

Ecological

- **Death of sessile animals:** Sessile animals, those that cannot move on their own, are prevalent along intertidal zones. During beach nourishment, these animals are either smothered or buried, causing immediate death from the impact of the sediment or subsequent mortality from lack of food. The mass die-off of these organisms after beach nourishment causes a trophic cascade as animals higher up the food chain struggle to find enough prey (Miselis et al. 2021).
- **Increase in water turbidity:** Beach nourishment can cause turbidity both at the mine site and the target beach. When sediment is mined, it disrupts the surrounding water and causes large amounts of sediment to become suspended in the water, increasing turbidity. At the target beach, turbidity increases when wave energy hits the sediments as they are being deposited, carrying excess sediment out with the current (Greene 2002).
- **Degradation of sediment source habitats:** When sediment is dredged from offshore or inlet sources, it can have detrimental impacts to the benthic communities that inhabit the dredging sites. Dredging causes mass mortality and decreased diversity as a result of the lack of sediments (Miselis et al. 2021). Inland sand mining has negative environmental impacts as well, reducing habitat, increasing sediment transport, and adding to carbon emissions by requiring thousands of truck trips (Dobkowski 1998).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size, mi	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Buxton Beach Nourishment Project	Cape Hatteras National Seashore, Buxton, NC	**National Park Service (NPS);** Dare County, NC	Sediment dredging from offshore sources	2.9	18,106,674	6 weeks	Contractor Great Lakes Dredge & Dock Co. used the dredger *Ellis Island* to deposit 1.2 million y^3 of sediment along the beach.	Sea level rise, coastal flooding, increasingly severe storms	Project was paused as the *Ellis Island* suffered mechanical issues and had to be repaired.
North End Restoration Project	Assateague Island National Seashore, MD	**NPS;** Maryland Department of Natural Resources; Worchester County, MD	Sediment dredging from offshore sources	5.9	12,653,540	18 years (spans 4 nourishment events)	The north end of Assateague Island was at risk of disappearing from the urbanization of nearby Ocean City, MD, and the construction of a jetty that blocked sediment transport. Beach nourishment has helped restore the island and protect endangered species habitat.	Sea level rise, coastal flooding, increasingly severe storms	After severe storms in 1998, officials placed an emergency storm berm along the shore to protect the island until beach nourishment could occur.
Ocean Beach Nourishment Project	Golden Gate National Recreation Area, San Francisco, CA	**NPS,** USACE, City of San Francisco	Reusing sediment dredged to increase channel navigability	0.57	13,370,000	Not provided	Contractors constructed dunes and placed sediment onto the beach using a hopper dredge.	Sea level rise, coastal flooding	Crews worked on the project 24/7 because the source of the sediment, dredging to deepen the San Francisco ship channel, never stopped.

Name and Link	Location	Leading Organizations	Techniques Used	Size, mi	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
South Padre Island Beach Nourishment Project	South Padre Island, TX	**US Geological Survey**, Coastal Texas Program, Town of South Padre Island, Texas General Land Office, USACE	Reusing dredged sediment, transporting sediment via trucks	2.9	27,365,044	24 years (spans 13 nourishment events)	Sediment reused from dredging nearby shipping lanes was deposited on the beach. Additionally, sediment that blocked a local highway was removed and transported to the beach.	Sea level rise, coastal flooding, increasingly severe storms	Because of frequent storms and high rates of erosion, renourishment has occurred at an extremely quick interval.
Sandy Hook Beach Nourishment Project	Gateway National Recreation Area, NJ	**NPS;** USACE; Monmouth County, NJ	Sediment dredging from offshore sources	21	414,028,787	59 years (spans 16 nourishment events)	The latest nourishment cycle, which costs $26 million, involves dredging sand to the eroding beach in the largest beach nourishment project ever undertaken.	Sea level rise, coastal flooding, increasingly severe storms	Every batch of sediment must be inspected for unexploded munitions, given that this area was once an army training ground.
Dade County Beach Erosion and Hurricane Protection Project, Miami Beach Renourishment	Miami Beach, FL	USACE, City of Miami Beach	Trucking in sediment from an upland sand mine	9.3	87,889,481	40 years (spans 37 nourishment events)	To restore one of America's most well-known beaches, contractors have trucked in around 17 million y^3 of sand over the course of 40 years to help sustain the beach.	Sea level rise, coastal flooding, increasingly severe storms	Sea turtle nests were relocated to protect them from the impacts of the project.

Bolding indicates DOI affiliates.

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Coastal Habitats
3. Coastal Marsh Restoration

DEFINITION

Coastal marshes, also frequently called *salt marshes*, are partially flooded wetlands that are inundated by salt water brought in by the tides but can vary in salinity levels (NOAA 2023). They occur where fine sediments accumulate along shoreline protected from the open ocean. Halophytes (salt-tolerant species) dominate the ecosystem, especially smooth cordgrass and saltmarsh hay on the Atlantic and Gulf coasts and American glasswort, California cordgrass, and big bulrush on the Pacific Coast of the United States (Zedler et al. 2008). Around half of coastal marshes globally have been lost or significantly degraded (DiGiacomo 2020). Prominent drivers of this decline include polluted stormwater runoff, erosion, invasive species, drought, and sea level rise (Morganello 2021). Coastal marsh restoration varies regionally, but typically includes isolating an area via dikes and pumping in sediment, planting native vegetation, and diverting nearby rivers to flow through the marsh (Olander et al. 2021).

TECHNICAL APPROACH

While coastal marsh restoration techniques vary, the following three steps are generally used to restore the marsh's structure and function to a more natural state:

1. **Restoring tidal exchange by removing any existing dikes and excavating canals and culverts Billah et al. 2022):** In many cases, the entirety of the dike does not need to be removed, but only breached in strategic spot. This will allow tidal inundation of the marsh, facilitating better conditions for salt marsh plants to grow (Hood 2004).

2. **Adding sediment to restore natural sediment characteristics and the marsh's elevation profile (Figure 1):** Organic soils, often from mangroves, are sometimes mixed into the existing topsoil to restore sediment characteristics (Billah et al. 2022), and dredged sediment from nearby channels can be used to build up marsh elevation (Kutcher et al. 2018). Using the sediment gathered during these projects for salt marsh restoration helps limit the cost of dredging sand. It also lessens the environmental impact of dredging and reduces the amount of dredged material in landfills (USACE n.d.).

3. **Vegetative restoration to remove invasive species, if necessary (Xie et al. 2019), and revegetation with native species, most commonly *Spartina* spp. and *Juncus roemerianus* along the Eastern seaboard of the United States (Craft et al. 2003):** One of the most prevalent invasive species in coastal marshes, the common reed (*Phragmites australis*), cannot grow in anoxic or high salinity conditions (Bart and Hartman 2002). In addition to promoting unfavorable conditions

for *Phragmites,* mechanical removal, applying herbicides, mowing, grazing, flooding the area, or prescribed burns can be used to repel invasions (Hazelton et al. 2014). Once invasive species removal is completed, replanting of native salt marsh plants can occur (Figure 2). While many planting strategies can be used, plugs (young plants grown in individual containers) or field transplants are the most effective methods (Rabinowitz et al. 2023).

OPERATIONS AND MAINTENANCE

Restored coastal marshes are likely to need periodic invasive species removal and may require occasional replanting with native species.

Figure 3.1 Adding sediment to Maidford Marsh at Sachuest Point National Wildlife Refuge in Rhode Island

Photo courtesy US Fish and Wildlife Service, Northeast Region

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Low elevation gradient (shallow slope):** Allows tidal flooding and generally promotes restoration success (NOAA 2023, Wolters et al. 2008).
- ✓ **Hydrodynamics:** Should allow for tidal exchange to reach most of the marsh, but marshes must be relatively sheltered from high-energy waves and strong currents, which will destabilize the vegetation (Steinigeweg et al. 2023).
- ✓ **Elevation within the tidal frame:** Ideally, restoration sites occur between the mean high water of neap tides and the level of the highest astronomical tides (Balke et al. 2016).
- ✓ **High salinity:** Baseline salinity levels of the surrounding waters must be conducive to salt marsh plants—generally between 18 and 35 ppt, depending on the elevation within the marsh (Odum 1988).
- ✓ **Sedimentation:** Sediment availability influences the marsh's ability to keep pace with rising sea levels caused by climate change, depending on the rate of increase (IPCC 2007). Measuring all sediment fluxes in the marsh is the best indicator of marsh resilience to sea level rise (Fagherazzi et al. 2020).
- ✗ **High wave energy:** Wave energy greater than 1.2 m/s will prevent plant growth (van Loon-Steensma et al. 2012).

Figure 3.2 Newly planted salt marsh cordgrass in Chesapeake, VA

Photo courtesy US Army Corps of Engineers, Norfolk District

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?
New York City Parks Salt Marsh Restoration Design Guidelines	Guidebook	2018	City of New York Parks & Recreation	Written for New York City based on New York State restoration guide but most information is more broadly applicable	Detailed guide to planning, design, construction, and maintenance of constructed and restored salt marshes. Intended as a how-to guide for those new to marsh restoration or as a reference for experienced practitioners.	✓	✓	✓	—
Salt Marsh Restoration Handbook: Britain & Ireland	Guidebook	2021	Environment Agency (United Kingdom)	Written for salt marshes in Britain and Ireland but most of the information is more broadly applicable	Detailed guide about site selection, project planning, benefits calculation, community engagement and construction and monitoring of restored salt marshes. Intended to provide practical guidance to those restoring or creating salt marsh habitat.	✓	—	✓	—
New York State Salt Marsh Restoration and Monitoring Guidelines	Guidebook	2000	New York State Department of Environmental Conservation	Written for the Northeast region but most information is more broadly applicable	Guidance document that details the characteristics of salt marsh habitat, human disturbance, and restoration and monitoring methods. Intended to provide a framework for salt marsh restoration and address common shortcomings in past projects.	✓	✓	✓	—
Gulf of Maine Association Project Planning: Salt Marshes	Website	n.d.	Gulf of Maine Association	Written for the Northeast region but most information is more broadly applicable	Overview webpage outlining funding, restoration techniques, invasive species removal, design considerations, and potential obstacles to restoration. This resource focuses on practical concerns, such as finding contractors and funding opportunities.	✓	✓	✓	✓

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Handbook for Restoring Tidal Wetlands	Guidebook	2001	Joy B. Zedler, Ed.	Applicable nationally, though all the case studies are from California	A technical guide focused on the details of coastal marsh restoration. Section topics include setting restoration goals, wetland topography and soils, planting vegetation, fish, invertebrates, and using geographic information system in salt marsh restoration.	✓	✓	✓	✓
Saltmarsh Management Manual	Guidebook	2007	UK Environment Agency	Written for salt marshes on the British Isles but most of the information is more broadly applicable	Guidance document to help maintain a healthy salt marsh for years after restoration has been completed. Topics covered include managed realignment, management techniques, and measuring change.	✓	—	✓	—
Maintaining Salt Marshes in the Face of Sea Level Rise—Review of Literature and Techniques	Guidebook	2019	US Army Corps of Engineers (USACE)	National	Review of salt marsh restoration practices with a special emphasis on adaptative management for sea level rise. Topics covered include erosion reduction, modelling sea level rise, and engineering considerations for salt marsh restoration.	✓	—	✓	—

GRAY INFRASTRUCTURE ALTERNATIVES

Coastal marsh restoration can be an alternative to gray infrastructure approaches that address coastal flooding and erosion, such as dikes, seawalls, and breakwaters. The ability of a coastal marsh restoration project to replace or supplement these gray infrastructure approach 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 coastal marsh restoration. See the gray infrastructure alternative tables in Section 1 for a comparison of salt marsh restoration to these alternatives.

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Reduced flooding:** Studies have shown coastal marshes can reduce the height of large waves by as much as 18%, making them a vital defense against storm surges (Moller et al. 2014). Coastal marshes limit coastal flooding by providing a greater linear distance between the open ocean and anthropogenic development. This is paired with marshes' ability to attenuate floodwater, with one acre of marsh able to hold up to one million gallons of water (Shepard et al. 2011). Coastal marshes also promote shoreline stabilization, where the vegetation traps sediments and increases the elevation of the coast.
- **Storm protection:** When large storms hit the coast, coastal marshes can absorb significant amounts of water, thus reducing inland flooding and associated property damage (Narayan et al. 2017).
- **Sea level rise adaptation and resilience:** Coastal marshes can continue to add elevation due to the accumulation of sediments, therefore protecting other habitats and developed areas behind the salt marsh from increased flooding due to sea level rise (Baustian et al. 2012). However, this process depends on the marsh being adequately vegetated, which coastal marsh restoration can bolster.
- **Carbon storage and sequestration:** Coastal marshes have anaerobic soil, meaning that organic carbon is broken down over a longer period and therefore kept out of the atmosphere (NOAA 2023).

Social and Economic

- **Property and infrastructure protection:** Intact coastal marshes provide a buffer for the coast against storm surge by absorbing much of the water and wave energy (Mason et al. 2018).
- **Mental health and well-being:** Coastal marshes can serve as public green space, which helps improve residents' mental health.
- **Resilient fisheries:** Because coastal marshes reduce algae blooms, increase the primary productivity of phytoplankton, and serve as nursery habitat for many gamefish species, they also increase the populations of both finfish and shellfish, increasing opportunities for harvest.

- **Food security:** Increased availability of fish and shellfish for harvest provides food security for residents who rely on wild harvest for a part of their food supply.
- **Recreational opportunities:** Coastal marsh restoration makes an area more suitable for many recreational activities, including kayaking, bird watching, and fishing.
- **Jobs:** Workers will need to be hired to perform the restoration activity, boosting the local economy.
- **Increased property values:** Studies have shown that property values increase as the amount of coastal marsh preserved on the property also increases (Gardner 2021).
- **Cultural values:** Coastal marsh restoration can increase local knowledge of the marsh ecosystem and provide aesthetic values that increase sense of place.

Ecological Benefits

- **Improved water quality:** Coastal marsh habitat traps sediments that flow across the marsh, reducing the turbidity of nearby waterbodies. Coastal marshes also prevent excess nutrients, like nitrogen, from entering nearby waterbodies. As less nutrients are available, the severity of algae blooms will decrease. Reducing algae blooms protects water quality by increasing dissolved oxygen and reducing the concentration of toxins produced by algae (Mason et al. 2018)
- **Increased primary productivity:** Because the water is less turbid, more light will penetrate further below the surface, resulting in an increase in phytoplankton primary productivity (Mason et al. 2018).
- **Supports wildlife:** Phytoplankton are the base of the food chain and support many fish species that will benefit from the increase in primary productivity.

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 barriers specific to coastal marsh restoration are included here.

- **Expense:** Thin-layer placement of dredge material is expensive because dredge material is heavy and cumbersome to transport. There must be suitable material near to the restoration site for projects using dredged sediment to rebuild marsh elevation to be economically viable. Many projects have used material dredged from widened shipping lanes (TNC 2023).
- **Capacity**
- **Public opinion**
- **Conflict with other land uses:** Community members may oppose coastal marsh restoration due to the mutually exclusive nature of wetland conservation and property development. However, properties built on historical coastal marshes have a high risk of flooding.

- **Regulation**
- **Lack of effectiveness data**

Ecological

- **Invasive species:** Even after a coastal marsh has been restored, it is common that invasive species will recolonize the area.
- **Sea level rise:** Although the natural process of sedimentation allows for coastal marshes to gain elevation, this is often outpaced by sea level rise (Fagherazzi et al. 2020). When marsh plants become submerged for long periods of time, they die off (Schuerch et al. 2013). This can limit the longevity of salt marsh restoration projects.
- **Diversity and function:** Restored salt marshes may struggle to achieve the same level of species diversity as they did before anthropogenic degradation occurred. This lack of diversity also has the potential to reduce certain wetland functions. However, this may only be a temporary phenomenon, with some marshes taking more than a decade to recover (Callaway 2005).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Great Meadows Restoration Project	Steward B. McKinney NWR, Stratford, CT	National Oceanic and Atmospheric Administration, **US Fish and Wildlife Service (USFWS)**	Increasing marsh elevation using dredged sediment	34	4.65 million	10 months	USFWS increased the marsh elevation by adding sediment, constructed tidal channels to restore tidal exchange, removed invasive species and planted native vegetation.	Sea level rise, increased storm severity	Tidal channels are needed to ensure that native turtles and fish can successfully enter the salt marsh.
Herring River Tidal Restoration Project	Cape Cod National Seashore, MA	**National Park Service (NPS), USFWS**	Dike removal to restore tidal exchange, invasive species and debris removal	1,100	60 million	4 years (expected)	To restore the tidal exchange that feeds salt marshes around the Herring River, workers are removing a dike that blocked the tidal exchange and replacing it with sluice gates. Debris and invasive species removal will also occur.	Sea level rise, increased storm severity	Significant controversy about changing a freshwater habitat back to a brackish one kept this project in the planning stage for decades.
The Nature Conservancy (TNC) Middle Township Restoration Project	Middle Township, NJ	TNC	Increasing marsh elevation using dredged sediment	60	Not provided	2 years	TNC used dredged sediment that was being removed to deepen a waterway to increase the elevation of salt marshes. This protects them against sea level rise.	Sea level rise, increased storm severity	Collaborating with other agencies to see if sediment is being dredged for other reasons helps reduce the cost of acquiring sediment.

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Assateague Island Restoration Project	Assateague Island National Seashore, MD and VA	**NPS**	Refilling ditches during the 20th century and installing native plants	400	Not provided	3 years	Workers filled in ditches that were created in a failed attempt to eradicate mosquitos from the island. This restored the hydrology and native plants were installed to boost the ecosystem's recovery.	Increased storm severity	It is important to use low impact equipment in delicate and often remote restoration sites.
Jamaica Bay Restoration Project	Gateway National Recreation Area, New York City, NY	**NPS,** USACE, New York State Department of Environmental Conservation	Increasing marsh elevation using dredged sand and installing native plants	62	11.5 million	3 years	To reverse the pervasive decline of this salt marsh due to sea level rise, workers raised the elevation using dredged sand and planted native vegetation.	Sea level rise, increased storm severity	Fencing was needed to protect the plantings from foraging geese.
Seal Beach Restoration Project	Seal Beach NWR, CA	**USFWS, US Geological Survey,** USACE	Increasing marsh elevation using dredged sediment	14	3.3 million	1 year	A 10-inch-thick layer of dredged sediment was placed on the salt marsh to keep up with sea level rise.	Sea level rise	A hay bale encircled the restoration site to prevent sediment runoff.
Ni-les'tun Marsh Restoration Project	Brandon Marsh NWR, OR	**USFWS,** Confederated Tribes of the Siletz	Excavated tidal channels, removed dikes and tidal gates	400	10 million	2 years	Workers filled in irrigation canals and dug natural tidal channels. Next, they removed tide gates and dikes to reconnect the marsh.	No	Restoration had to be paused multiple times as items of archeological significance were found on the site.

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Long Island Restoration Project	Wertheim, Seatuck and Lido Beach NWRs, Long Island, NY	**USFWS**	Excavated tidal channels, filling in mosquito ditches, installing coir logs	567	8.23 million	3 years	USFWS began this initiative as a response to the intense damage that Hurricane Sandy caused. Workers excavated channels, installed coir logs, filled mosquito ditches, graded dredge material, removed invasive species and planted native species.	Sea level rise, increased storm severity	Even after restoration, control measures for *Phragmites australis* were still needed.
Oxnard Restoration Project	Oxnard, CA	**Reclamation,** City of Oxnard, TNC	Constructed surface flow wetland near wastewater discharge site	1,000	55 million	3 years	In an experiment to streamline the city's wastewater treatment facility, the City of Oxnard have restored salt marshes near a wastewater discharge site to purify the water naturally.	Drought	Despite the large amount of waste entering the salt marsh, the plants can mask the odor.

Bolding indicates DOI affiliates.

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Coastal Habitats
4. Coral Reef Restoration

DEFINITION

Coral reefs are the skeletons of marine invertebrates called *coral*, which form large underwater structures comprised of colonies. Coral reefs are built by hard corals that extract calcium carbonate from the ocean to create an exoskeleton (Ross 2018). Coral polyps, which are individual corals, begin building reefs by attaching themselves to submerged rocks or hard surfaces near the ocean floor (CRA 2018). In most cases, coral reefs are constrained to shallow waters and latitudes between 30° north and south of the equator (NOS n.d.). In the United States, corals are concentrated in the Pacific Islands, the Caribbean, and the Gulf Coast, with a few isolated deep-sea corals off the Pacific and Carolina coasts (Necaise et al. 2022; Oceana n.d.). Coral reefs are sensitive ecosystems facing many threats, including ocean acidification, increases in water temperatures, pollution, and physical damage (EPA 2023). Coral reef restoration strategies include direct transplantation, coral gardening, invasive species removal, micro-fragmentation and building artificial reefs (Boström-Einarsson et al. 2020).

TECHNICAL APPROACH

Because coral grows slowly, innovative techniques are needed to restore coral reefs at a large scale (Dullo 2005). Coral restoration techniques include methods for removing stressors to existing reefs, enhancing the reef structure, and supplementing the coral population. These techniques are often used in conjunction with each other and none of the methods are mutually exclusive.

1. **Removing stressors to existing reefs:**
   - **Predator removal:** Native predators of coral, such as the crown-of-thorns starfish (*Acanthaster planci*) and the burrowing urchin (*Echinometra mathaei*), have proliferated because of the overfishing of their natural predators and increases in nutrient runoff, which aid starfish in their planktonic stages. Excess numbers of these predators have deleterious effects on corals and can wipe out entire colonies (Goldberg and Wilkinson 2004). Removal strategies include physically removing or chemically injecting the animals (KSLOF n.d.).
   - **Algae removal:** Significant algae buildup can occur in coral reefs that are inundated by nutrient pollution. Algae shade coral, transmit pathogens, and release chemicals that block coral growth, all of which degrade coral health. To remove excess algae, introduction of herbivorous fish and physical removal are the most established control methods (Ceccarelli et al. 2018).
   - **Disease management:** Multiple diseases plague coral, most notably black band disease in coral reefs in the Caribbean and the Gulf of Mexico. While research on

controlling coral pathogens is limited, two main treatment options are available: phage therapy and probiotics. Phage therapy uses bacteriophages that prey on coral pathogens while probiotics introduce mutualistic bacteria that compete with the pathogens (Teplitski and Ritchie 2009).

- **Invasive species removal:** Invasive species vary geographically across American coral reefs, with prominent invaders including corallimorphs (*Corallimorpharia*), and lionfish (*Pterois*). Treatments vary from species to species, with innovative approaches like toothpaste application and boiling seawater particularly effective at subduing noxious corallimorphs (Work et al. 2022).

2. **Enhancing reef structure:**

   - **Building artificial reefs (substrate enhancement):** Building artificial reefs adds additional hard substrates to a degraded reef, improving coral habitat and giving coral polyps something to latch onto. Building materials used include eco-friendly concrete, reef balls, construction rubble, and modular hexagonal structures called *spiders*. Artificial reefs help protect corals from harmful fishing practices like bottom trawling (Fadli et al. 2012), because artificial reefs can break nets used in bottom trawling, deterring fishing boats from entering the area (Liu et al. 2011).

3. **Supplementing the coral population:**

   - **Direct transplantation:** *Coral transplantation* refers to the relocation of coral fragments or colonies from a healthier donor reef to a reef experiencing significant stress or degradation (Figure 1; Ferse et al. 2021). Donor reefs are often planned to be destroyed by construction projects and the corals are salvaged to aid other reefs (Boström-Einarsson et al. 2020). Direct transplantation is a controversial restoration strategy because virtually all coral reefs globally are in distress, making it difficult to find donor reefs. Transplantation should be used as a last resort when the reef fails to recruit juvenile corals (Edwards and Clark 1999).
   - **Coral gardening:** Coral gardening involves taking coral recruits and raising them in protected nurseries, which helps increase coral survival rates (Figure 2). Nurseries can either be in the open ocean or closed holding tanks. Once the corals have grown to a size where their survival rates are higher, they are placed at the degraded reef site (Rinkevich 2005)
   - **Microfragmentation:** Microfragmentation involves breaking up corals into tiny pieces, which helps them grow faster. This allows for a greater amount of coral to be available for restoration projects without taking more coral from natural reefs. Microfragmentation must occur in a controlled environment because coral fragments are much more vulnerable to predation (Page et al. 2018). Microfragmentation is often paired with coral gardening (Boström-Einarsson et al. 2020).

Figure 4.1 Transplanted elkhorn coral near Puerto Rico

Photo courtesy NOAA's National Ocean Service

Figure 4.2 A coral nursery growing staghorn coral on a tree structure

Photo courtesy NOAA's National Ocean Service

- **Larval enhancement:** Corals produce millions of offspring, but few corals make it to adulthood (Boström-Einarsson et al. 2020). There are multiple pioneering methods of larval enhancement, including the use of harvested gametes to raise embryo corals in a protected environment and then releasing the corals to degraded sections of a reef (dela Cruz and Harrison 2017).

OPERATIONS AND MAINTENANCE

Invasive species removal using the techniques described previously is often required on an ongoing basis after coral reef restoration. Additional repairs to the restored reef may be needed after severe storms, and the metallic tools and dive equipment used for maintenance must be cleaned. If a coral nursery is used to supply the project with new coral recruits, it must be maintained as well.

FACTORS INFLUENCING SITE SUITABILITY

✓ **Adequate room to accommodate colony expansion:** Once a coral colony becomes established, it should be able to naturally expand over time. Selecting a site with adequate room will help facilitate this process (Johnson et al. 2011).

✓ **Near existing wild populations:** Wild coral populations serve as a proxy for ideal conditions for coral growth. Additionally, wild coral populations can help increase genetic diversity in restored coral colonies (Johnson et al. 2011).

✓ **Ample sunlight:** Corals rely on photosynthetic algae for survival. Sunlight needs to penetrate down to the reef to provide energy for the whole ecosystem (Johnson et al. 2011).

✓ **Hard and stable substrates:** Hard substrates reduce sedimentation (which lowers turbidity and allows sunlight to filter deeper into the water) and competition from other species. Stable substrates give corals a secure surface to latch onto (Johnson et al. 2011).

✓ **Historical presence of coral reefs:** Corals reefs are limited to particular areas due to their specific requirements for water depth, temperature, and pH. Choosing a site where historic coral populations once thrived increases the likelihood that a site will be suitable for coral restoration (Tsang et al. 2020).

✗ **High temperature variability:** Mass coral die-offs are often associated with rapid fluctuations in temperature. Choosing areas with stable year-round water temperatures will reduce the stress on corals.

✗ **High human impacts that won't be reduced as part of the project:** Sites that are frequented by boats, industry, and dredging are not ideal for coral reefs. Most coral restoration projects occur inside marine protected areas (MPAs) or in remote areas (Shaver et al. 2020).

✗ **High levels of coral predation:** Unless coral predators are being removed as a part of the restoration project, it is a waste of resources to restore a coral reef without addressing the cause of its degradation. Predation is one of the key determinants of coral survivorship. Few corals are likely to survive unless predator populations are first reduced (Shaver et al. 2020).

- **High water movement:** Corals thrive in areas where the water is relatively calm. Corals will struggle to establish themselves in areas with strong currents (Johnson et al. 2011).
- **Near areas with excessive pollution discharges:** Nutrient and sediment pollution from terrestrial sources limit coral growth. Limiting the sources of pollution is necessary before engaging in coral restoration.

TOOLS, TRAINING, AND RESOURCES FOR PLANNING AND IMPLEMENTATION

						Resource Includes			
Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Coral Reef Restoration as a Strategy to Improve Ecosystem Services	Guidebook	2021	UN Environment Programme	Global	This guidebook gives a broad overview of coral reef restoration and the situations for which it is applicable. The resource contains recommendations for implementing a project as well as six case studies of successful projects.	✓	—	✓	✓
A Manager's Guide to Coral Reef Restoration, Planning and Design	Guidebook	2020	National Oceanic and Atmospheric Administration	National	This guidebook helps restoration managers choose suitable sites for restoration and develop effective restoration strategies. The authors put an emphasis on matching the applicable restoration strategies with an appropriate site for that strategy.	✓	✓	✓	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Caribbean *Acropora* Restoration Guide: Best Practices for Propagation and Population Enhancement	Guidebook	2011	Nova Southeastern University	Caribbean and Gulf of Mexico	Focused on reefs dominated by *Acropora* corals, this guidebook covers coral gardening and other restoration techniques. A special emphasis is given to increasing genetic diversity within coral colonies.	✓	✓	—	✓
Coral Reef Restoration Toolkit	Guidebook	2018	Nature Seychelles	Designed for Seychelles but most of the information is more broadly applicable	This practical guide explains the nuances of coral reef restoration, providing details about the equipment and resources needed to complete a project. The authors also enumerate successful practices for coral gardening and coral transplantation.	✓	✓	✓	—
Training Guide for Coral Reef Restoration	Guidebook	n.d.	Mesoamerican Reef System Reef Rescue Initiative	Designed for the Caribbean and Gulf of Mexico but most of the information is more broadly applicable	Designed to aid specialists with coral restoration, this guide describes procedures associated with asexual and sexual coral rearing techniques. The authors also weigh the trade-offs of different coral gardening methods and discuss coral fragmentation.	✓	✓	—	—
Hawaii Division of Aquatic Resources Coral Restoration Implementation Guide	Guidebook	2019	Hawai'i Division of Aquatic Resources	Designed for Hawai'i but most of the information is more broadly applicable	This resource focuses on mitigating risks associated with coral transplantation. Topics covered include disease transmission, ecological concerns, and genetic considerations.	✓	✓	—	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Coral Reef Restoration Monitoring Guide	Guidebook	2020	National Oceanic and Atmospheric Administration (NOAA)	National	Monitoring is an integral component of every coral restoration project, making this guide especially valuable to coral restoration project managers. This resource lays out metrics for environmental, ecological, socioeconomic, and coral health.	—	—	✓	—
Coral Reef Restoration: The Rehabilitation of an Ecosystem under Siege	Book chapter	2005	William Precht and Martha Robbart	National	This guide focuses on identifying the agents of coral reef degradation and developing a plan to mitigate these drivers of decline. The authors provide information on identifying signs of reef decline to inform the creation of relevant restoration goals.	✓	✓	✓	—
Coral Reef Restoration for Risk Reduction (CR4): Guide to Project Design and Proposal Development	Guidebook	2022	University of California Santa Cruz	National	Containing information about designing coral reef restoration projects specifically for reducing flood risk, this guide provides the key components needed to make a project successful. The authors outline federal funding available for coral reef restoration projects, including advice about the application process.	✓	✓	—	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Handbook on Coral Reef Impacts: Avoidance, Minimization, Compensatory Mitigation, and Restoration	Guidebook	2016	US Coral Reef Task Force	National	This guide encompasses a variety of coral reef damage mitigation strategies, including ways to remediate the impacts of oil spills, dredging, sedimentation, and pollutant-laden stormwater runoff. The guide also contains a comprehensive list of all federal statutes that apply to coral reefs.	✓	✓	✓	—

GRAY INFRASTRUCTURE ALTERNATIVES

Coral reef restoration can be an alternative to gray infrastructure approaches that address coastal flooding and erosion: artificial breakwaters, riprap/revetments, seawalls, bulkheads, and groins. The ability of a coral reef 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 coral reef restoration. See the gray infrastructure alternative tables in Section 1 for a comparison of coral reef restoration to these alternatives.

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Storm protection:** As severe storms become more frequent with climate change, coral reefs provide vital protection to coastal communities, preventing billions of dollars in storm damage. During intense storms, shallow coral reefs and those near the coast were found to be the most effective at mitigating storm damage, meaning that these reefs should be prioritized for restoration (Beck et al. 2018).

- **Reduced flooding:** Corals reefs are highly effective at wave attenuation, dissipating wave energy before the water reaches the coast. This reduces coastal flooding because as large waves cross coral reefs, their height rapidly decreases, preventing water from penetrating inland (Roelvink et al. 2021).
- **Sea level rise adaptation and resilience:** Historically, coral reef expansion was limited by sea level, with corals not able penetrate water's surface. Presently, sea level rise has allowed coral reefs to expand vertically. Coral reef growth can keep pace with moderate sea level rise as long the reef remains healthy, providing a bulwark of protection to vulnerable coastal communities (van Woesik et al. 2015). Coral growth may not be able keep up with very rapid sea level rise, which causes coral decline resulting from the lack of sunlight for photosynthetic algae that aid coral survival (Sanborn et al. 2017).
- **Carbon storage and sequestration:** Corals serve as carbon sinks, storing carbon via the process of calcification. Corals build their skeletons with calcium carbonate, which stores carbon for long periods of time. Coral restoration hastens the pace of calcification, enhancing a reef's ability to serve as a carbon sink (Platz et al. 2020).

Social and Economic

- **Recreational opportunities:** Coral reefs are key locations for recreational activities including scuba diving, snorkeling, and kayaking.
- **Tourism:** Tour companies have been the drivers behind coral reef restoration projects in many regions, especially the Caribbean. Because tour companies rely on healthy reefs to continue attracting tourists, they are willing to expend significant capital on coral reef restoration. Furthermore, tour companies can have greater financial resources than government agencies or nongovernmental organizations, which help underwrite the hefty costs of coral reef restoration (Blanco-Pimentel et al. 2022). While the impacts of tourism can degrade coral reefs, sustainability measures can help mitigate these downsides (Cowburn et al. 2018).
- **Reduced erosion:** Coral reefs help reduce shoreline erosion by attenuating waves and protecting and retaining sand for beach nourishment. Intact coral reefs are necessary to stabilize shorelines, with areas of significant reef degradation also experiencing high rates of erosion (Reguero et al. 2018).
- **Property and infrastructure protection:** Because of their ability to shield coastal properties, the coastal protection value of coral reefs is estimated at $9 billion worldwide (van Zanten et al. 2014). This protection is especially valuable in the Caribbean and Pacific Islands, where many industries depend on access to the water and need to be located on a waterfront property.
- **Food security:** Many subsistence fisheries rely on healthy coral reefs, meaning that coral reef restoration can boost local nutrition.
- **Resilient fisheries:** Studies have shown that restored coral plots host increased species richness than degraded plots. Fish colonization of degraded areas occurs rapidly after restoration, meaning fish harvesting can resume soon after a plot has been restored (Opel et al. 2017).

- **Jobs:** Coral reef restoration is a labor and equipment intensive process. Local workers will need to be hired to perform the restoration, stimulating the local economy.
- **Mental health and well-being:** Healthy coral reefs help enhance greenspace for the public to enjoy, improving mental health and psychological wellbeing.
- **Cultural values:** Coral restoration helps improve public knowledge of coral reefs, boosting awareness and connection to the ecosystem.
- **Scientific research:** Because corals are particularly vulnerable as stationary animals, they have developed a repertoire of chemical defenses to protect themselves. Species that reside in coral reefs are a source of medicines for cancer, Alzheimer's, and heart disease (NOS 2023).

Ecological

- **Enhanced biodiversity:** Coral reefs are the most biodiverse marine habitat, hosting 32% of all marine biodiversity despite only covering 0.1% of the ocean's surface area (UNEP n.d.). Despite the steep decline in biodiversity among the world's coral reefs, properly managed coral reef restoration has been shown to slow the loss of biodiversity (Rinkevich 2021).
- **Supports wildlife:** Coral reefs support fish species that spend most of their life cycles in the open ocean, having an outsized impact on marine biodiversity. Coral reefs provide protection for young fish, making them ideal spawning grounds. Fish abundance in restored coral reefs increases exponentially as the site ages, highlighting the effectiveness of coral restoration in fish conservation (Seraphim et al. 2020). More than 83 species of coral are listed as endangered under the Endangered Species Act and many other endangered animals reside in coral reefs as well (Gregg 2021). Coral reef restoration can help reverse this pervasive decline by facilitating the recruitment of endangered corals and restoring the reef structure to provide habitat for endangered animals (Lirman and Schopmeyer 2016).
- **Increased primary productivity:** Coral reefs have high rates of primary productivity because of their efficient nutrient cycling. Coral restoration helps maintain these biogeochemical processes, increasing primary productivity (Davis et al. 2021).
- **Improved water quality:** While coral reefs cannot tolerate poor water quality, corals can improve water quality via filtration. Corals feed on particulate matter, helping remove pollutants from the ocean (UNEP 2020).

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 these barriers specific to coral reef restoration are included here.

- **Expense:** Coral reef restoration is one of the most expensive habitats to restore, with restoration costs of up to $2,879,773 per hectare ($1,165,900 per acre) (Bayraktarov et al. 2016). Coral reef restoration requires high upfront investment capital, such as boats and nurseries to host coral gardening. However, the cost of restoration can vary widely depending on the technique used and location of the restoration site.

- **Capacity**
- **Public opinion**
- **Conflict with other land uses:** Many coral reefs have been degraded from bottom trawling, which destroys the structure of the coral reef. Most coral reef restoration sites are in MPAs, which limit or completely ban fishing (Armstrong et al. 2014). While healthy coral reefs can boost fish stocks, many fishermen may be opposed to increased regulations related to coral restoration projects. Coral mining, where coral is harvested for construction materials or as a source of calcium, is also detrimental to reef health. While the total economic value of a reef is far more than the economic gains from coral mining, mining is a vital source of income for many workers in developing areas (Guzmán et al. 2003).
- **Regulation:** There are many statutes, regulations, and policies to be cognizant of when planning a coral reef restoration project. These include the Abandoned Shipwreck Act, the Coastal Barriers Resources Act, the Coral Reef Conservation Act, and the Lacey Act, all at the federal level (EPA 2016). States, territories, and local authorities may have their own additional requirements. It is vital to line up all the necessary permits before construction begins because many grants will only support projects that have been fully approved (Stovall et al. 2022).
- **Lack of effectiveness data**

Community

- **Encroachment on the reef:** Local residents and tourists alike visit coral reefs for their aesthetic value. However, frequent visitation to reefs, especially during the restoration process, can kill corals. Therefore, local communities must be involved in the project planning process to encourage them in aiding the restoration process by temporarily refraining from visiting the reef (Hein et al. 2019).
- **Equitable access to coral reefs:** Many local communities often feel that coral reef restoration projects are meant to attract more tourists and not to help local residents. This sentiment often stems from no-take zones within parks and the high costs of coral restoration. Incorporating local knowledge and goals into the restoration project is vital to increasing compliance with park rules (Cinner et al. 2012).

Ecological

- **Challenges of mimicking natural reefs:** Artificial reefs struggle to mimic the original substrates that support a successful coral reef ecosystem. Because artificial reefs are large structures, substantial quantities of material must be found and transported out to sea to create an artificial reef. To defray these high costs, many projects have used construction rubble or other waste materials as a reef substrate, which often contains toxic materials (Svane and Petersen 2002).

- **Susceptibility to nutrient pollution:** Nutrient pollution reduces both calcification and production rates of coral reefs, reversing coral growth. Nutrient pollution reduces the metabolism of corals and alters the pH of reef waters, meaning that terrestrial fertilizer runoff must be reduced before a reef can achieve full health (Silbiger et al. 2018).
- **Ocean acidification:** Ocean acidification is caused by anthropogenic CO_2 emissions. About 25% of CO_2 emissions are absorbed by the ocean, where the excess CO_2 becomes carbonic acid. Through a chain of chemical reactions, the surplus carbonic acid creates more bicarbonate, which diminishes the amount of carbon that is available to corals, reducing calcification (Hoegh-Guldberg et al. 2007). In other words, as long as humans emit large quantities of CO_2, coral reefs will be at risk.

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Palmyra Atoll and Kingman Reef Coral Restoration Project	Palmyra Atoll and Kingman Reef National Wildlife Refuges, HI	**US Fish and Wildlife Service (USFWS)**, The Nature Conservancy, NOAA, US Environmental Protection Agency, US Coast Guard	Invasive species removal, shipwreck removal, coral transplantation	1	5.5 million	One month for debris removal, but ongoing invasive species treatment	The iron from shipwrecks fueled the growth of invasive species in the coral reef, particularly corallimorphs and algae. USFWS and partners removed the shipwrecks and invasive species, and transplanted corals to help the reef regenerate.	No	Corallimorph control must be incorporated into long-term management strategies, as treatment occurred for many years after the initial shipwreck removal.
Eastern Dry Rocks Coral Reef Restoration Project	Florida Keys National Marine Sanctuary, FL	NOAA, National Fish and Wildlife Foundation, Coral Restoration Foundation, Mote Marine Laboratory & Aquarium	Invasive species and debris removal, coral outplanting	69	5 million	Still ongoing—started in 2021	The project removed invasive species and other debris at the site. Then, divers planted more than 60,000 corals, mostly staghorn and elkhorn corals.	Sea level rise, increased storm severity, coastal flooding	NA
Carysfort Reef Restoration Project	Key Largo, FL	NOAA, Ocean Reef Club, Coral Restoration Foundation	Coral outplanting	31	4 million	5 years	Carysfort Reef was once one of the most vibrant reefs in the Florida Keys but succumbed to disease. Coral outplanting occurred on artificial reef structures.	Sea level rise, increased storm severity, coastal flooding	Artificial reef barriers and buoys are important to deter ships from entering the restoration site.

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
T/V MARGARA Ship Grounding Site	Bahia de Talloboa, PR	NOAA, Puerto Rico Department of Natural and Environmental Resources	Coral outplanting, reattaching loose corals, stabilizing corals	2	4.5 million	5 years	Coral outplanting occurred in the affected area, with corals supported by masonry nails, cable ties and epoxy. Corals that survived the incident were stabilized with stakes or wire cages.	No	Rubble needs to be completely cleared before the mortality rates of coral recruits will decrease.
Columbus Iselin Coral Reef Restoration Project	Florida Keys National Marine Sanctuary, FL	NOAA	Shipwreck removal, substrate remediation, artificial reef made with rebar and limestone boulders, coral outplanting	1	3.75 million	6 weeks	Debris, rubble, and damaged coral were removed from the site. Then, coral outplantings were placed on a new substrate of rebar and limestone boulders.	Increased storm severity	Coral restoration must occur all at once, as partially completed restoration projects are vulnerable to further degradation from hurricanes.

Bolding indicates DOI affiliates.

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Coastal Habitats
5. Dune Restoration

DEFINITION

Coastal dunes are large mounds of sand deposited on the landward side of a beach. Dune formation is reliant on coastal winds blowing in the onshore direction, allowing the sand to accumulate when it encounters an obstacle on the beach (Bralower et al. n.d.). Coastal dunes can be classified into *primary* and *secondary* dunes. Primary dunes are created by direct sand supply from the beach while secondary dunes are formed from alterations to the primary dunes and are located further landward. The highly variable processes of sand deposition, accretion, and erosion result in a diversity of dune morphologies, including blowouts, foredunes, parabolic dunes, and dune fields (Sloss et al. 2012). Dune vegetation, which often forms symbiotic relationships with fungi, helps stabilize the sand and reduce dune erosion (Charbonneau et al. 2016). Coastal dunes face threats from increased urbanization, beach erosion, conversion into developed areas, and shoreline hardening (Carboni et al. 2009). Dune restoration helps stabilize dunes to protect the valuable ecosystem services they provide. The most common dune restoration techniques include dredging sand to build up the dune, planting grasses, and installing fencing around the dune (Olander et al. 2021).

TECHNICAL APPROACH

Despite the constantly changing nature of coastal dunes, dune restoration aims to stabilize dunes by facilitating natural dune creation processes (UNH 2023). Dune restoration differs from beach nourishment in that it builds sand up vertically instead of horizontally. These techniques can be applied to already-existing dunes or can be used to build dunes from scratch. While each of the following techniques can be applied independently, the most successful projects combine multiple techniques (Olander et al. 2021).

1. **Building up dunes with sand:**
    - **Dredging sand:** Dredging sand from offshore sources and transporting it onto the beach via piping is a common dune restoration technique. Similar to beach nourishment, this method of dune restoration is dependent on the source sediment having similar qualities to the sediment on the dune (Nordstrom and Jackson 2021). In many aeolian (wind) regimes, high rates of erosion will require periodic renourishment to maintain the dune (Speybroeck et al. 2006). Dredging sand from offshore is only economically viable for large projects given the high cost of mobilizing a dredger, which can range from $500,000 to $1 million (Dean 2002). To reduce the environmental impacts of dredging and save costs, using sediment already being dredged to deepen channels is recommended. Called *beneficial use of dredged material*, this practice diverts dredged sediment from ending up in a landfill while creating a dune habitat (USACE n.d.).

- **Placing sand using heavy machinery:** For projects where dredging sand from offshore is impractical but sand nourishment is still needed because of a lack of natural sand deposition, placing sand using heavy machinery is an alternative. Sand mined from inland sources and taken to the restoration site can be used (Dobkowski 1998). It is not recommended that sand be extracted from adjacent beach areas, as this would alter sediment deposition patterns and disturb the long-term health of the coast (NCRS 2011). Once the sand has arrived at the beach, heavy machinery is used to sculpt the sand into a dune shape. Then, a small layer of natural dune sand, 3 to 6 in. thick, is placed on top of the imported sand (O'Connell 2008).

2. **Removing invasive species:** Many invasive species can be found on dunes, outcompeting native species, and causing a decline in biodiversity. While some invasive species were introduced to help stabilize dunes, their presence has altered natural sand flow processes. Although manual removal of invasive species is ideal, it is costly and labor intensive. Other control strategies include herbicide application, prescribed burns and burying invasive plants with excavators (Pickart et al. 2021). Common invasive species in dune ecosystems include European beachgrass (*Ammophila arenaria) on the West Coast, Asiatic sand sedge (Carex kobomugi) on the East Coast, and coastal she-oak (Casuarina equisetifolia*) on the Gulf Coast (Charbonneau et al. 2016; Pickart et al. 2021; NatureServe 2022).
3. **Planting dune grasses:** Dune grasses are critical for stabilizing the sand in the dune and supporting biodiversity (Johnston et al. 2023). Planting dune grasses is challenging because of the harsh and windy conditions. To establish a stable environment, placing mechanically crimped straw or biodegradable netting over straw provides a substrate for the plants to establish on (Pickart 1988). Planting design should mimic the natural dispersal of plants on nearby dunes, with clumped and dispersed planting designs displaying highly variable success rates based on their location (Woods et al. 2023). Plants can either be purchased as plugs (young plants grown in individual containers) or transplanted from nearby healthy dunes. Hand planting is recommended for areas with steep slopes, but tractor-drawn planters can be used in flatter areas (Figure 1; NRCS 2011). The species planted will differ by region, with the most common plantings being American beachgrass (*Ammophila breviligulata*) and sea oats (*Uniola paniculate*) on the East Coast, bitter panicum (*Panicum amarum*) and gulf cordgrass (*Spartina spartinae*) on the Gulf Coast and American dune grass (*Leymus mollis*) and beach bur (*Ambrosia chamissonis*) on the West Coast (Woods et al. 2023; Pickart 1988; Johnston et al. 2023; NRCS 2011). Planting later successional species may be a more effective way to stabilize the dune (Charbonneau et al. 2016).
4. **Installing fences around the dune:** Sand fencing helps trap sand deposited by the wind, building up the dune (Figure 2; NCCOS 2020). Sand fences lead to a shorter and wider dune complex compared to naturally occurring dunes, meaning that it may not be the appropriate intervention based on the desired dune morphology (Itzkin et al. 2020). Many projects only install fencing on three sides of the dune, leaving the seaward side unfenced to allow sand to blow into the dunes (Johnston et al. 2023). The type of fence used varies, but generally wood or plastic fencing ranging from 2 to 4 ft will suffice (OCRM n.d.). The fences must be secured in the dune to withstand

Figure 5.1 Planting dune grasses in Florida

Photo courtesy US Department of the Interior

Figure 5.2 Sand fencing on dunes in Alabama

Photo courtesy Alabama Extension

wind and erosion, with a minimum depth of 4 ft underground (O'Connell 2008). Fence placement is important, as the fences should be positioned beyond the range of storm tides but seaward of the toe of the dune scrap (OCRM n.d.). Multiple rows of fences can be used to increase stability (O'Connell 2008). Periodic breaks in the fencing should be considered to allow for the movement of sea turtles and other wildlife. In addition to aiding in sand accretion, fencing also limits pedestrian access to the dune (OCRM n.d.).

5. **Reducing beach grooming:** Beach grooming is when tractors grade the sand on beaches to smooth out any holes or debris. This practice is common on many urban beaches and improves the conditions for beach recreation. However, beach grooming is detrimental to beach biodiversity, with grooming eliminating wrack (clumps of seaweed) and the coastal strand zone from the beach (Dugan and Hubbard 2010). A form of passive restoration is to cease beach grooming and install sand fencing, allowing the dune to regenerate naturally. A buffer zone of around 4 to 5 m is recommended between grooming activities and the dune restoration site (Johnston et al. 2023).
6. **Avoid adverse impacts from beach access:** Pedestrian access boardwalks through the dune restoration site are critical to protecting the dune while maintaining public beach access. Boardwalks should be sited in a way that does not damage the dunes or require the movement of sand (OCRM n.d.).

OPERATIONS AND MAINTENANCE

Operations and maintenance of a dune restoration project is estimated to cost $100 to $500 per linear foot per year (NOAA 2020). This includes regular invasive species removal, restricting beach grooming, and inspecting and repairing sand fences and boardwalks after severe storms. In dry climates, dune plants may need to be watered. In areas with high erosion rates, sand may need to be added to the dunes periodically.

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Near existing dunes:** Existing natural dunes will give the new dunes greater protection from the elements as the plants get established on the new dune. Redundant dunes help increase the protection of inland development. This also works with landward beach migration resulting from sea level rise (O'Connell 2008).
- ✓ **As far as possible away from mean high water:** Building the dune further inland gives it greater protection from tidal erosion. It also prevents the vegetation from becoming inundated (O'Connell 2008).
- ✓ **Parallel to the beach berm:** The *beach berm*, or flat part of the beach, provides a buffer that absorbs wave energy and tidal fluctuations. Placing dunes parallel to the beach ensures that all of the beachfront receives similar levels of protection (Kidd 2001).
- ✓ **Straight morphology:** While natural dunes can have a variety of morphologies, restored dunes tend to have a straight, linear morphology (Nordstrom et al. 2000). Additionally, too many bends in the dune adds to fencing costs (Kidd 2001).

- ✓ **Windy conditions:** Dunes need wind to transport sand from the beach. A lack of wind will result in dunes being replaced by scrubland, as dune grasses need open and mobile conditions to compete (Pye et al. 2014).
- ✗ **Adjacent to seawalls, bulkheads, and groins:** Seawalls, bulkheads and groins cause erosion in adjacent areas. Additionally, hard shoreline armoring reduces sediment transport, making it difficult to build up a dune (McKann et al. 2021).
- ✗ **Heavy pedestrian or vehicle traffic:** Unofficial pedestrian or vehicle trails create gaps in the dunes. During a severe storm, these gaps may be exploited by a storm surge and cause a blowout, washout, or washover (McKann et al. 2021).
- ✗ **High grazing pressure:** Vegetation helps hold down the sand in the dune; a loss of vegetation from grazing can cause erosion. It is difficult to get vegetation to grow back under harsh conditions (McKann et al. 2021).
- ✗ **Major inflections in the seaward face of the dune:** Inflections in the seaward face of the dune will cause the wind to eddy and remove sand, facilitating erosion (Kidd 2001). If a natural dune shows this characteristic, it can be addressed in the restoration project design.
- ✗ **Narrow beaches:** Narrow beaches will not have enough space for both the beach berm and the dune. This will either cause the landward migration of the dune into upland (usually developed) areas or erosion of the dune from tidal exposure.
- ✗ **Arid regions:** Dune plants need a baseline level of precipitation to survive. This barrier can be outcome with intensive irrigation and fertilization.

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?
Beach and Dune Restoration	Guidebook	2022	Karl Nordstrom and Nancy Jackson	Global	This guide is a compilation of dune restoration knowledge, covering specific techniques as well as project planning and stakeholder engagement. Chapters three through eight are especially relevant to dune restoration practitioners.	✓	✓	✓	✓
Foredune Restoration in Urban Settings	Book chapter	2013	Karl Nordstrom and Nancy Jackson	National	Incorporating the natural dynamism in dune ecosystems into restoration projects is covered in the chapter, in addition to specific techniques. The authors also discuss the benefits involved with dune restoration and balancing restoration with recreation.	✓	—	✓	—
Coastal Dune Protection and Restoration	Guidebook	2008	Woods Hole Oceanographic Institution	East Coast	This guide covers the main dune restoration techniques as well as helpful graphics to visualize the restoration process. Additional topics covered include maintenance, conserving shorebird habitat, and managing pedestrian use.	✓	—	—	✓
Coastal Dunes: Dune Protection and Improvement Manual for the Texas Gulf Coast – 6th edition	Guidebook	2021	Texas General Land Office	Gulf Coast	Focusing on the role that dunes play in the larger coastal system, this guide details the techniques of dune construction, improvement, and repair. A special emphasis is placed on maintaining beach access, including the construction of dune walkovers.	✓	✓	—	✓

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Coastal Shoreline and Dune Restoration: Plant Materials Technical Note	Document	2011	Natural Resources Conservation Service (US Department of Agriculture)	Gulf Coast	This technical note gives information about planting designs, the qualities of dune species and planting techniques. Additional topics covered include fencing installation and site management.	✓	—	—	—
Sand Dune Conservation, Restoration, and Management	Guidebook	2013	J. Patrick Doody	Global	Covering the ways in which human activity has altered sand dunes, this book gives a comprehensive overview of the geomorphic, policy, and ecological considerations that impact dune restoration. The authors also cover best management practices, invasive species, and interactions between dunes and the urban environment.	✓	✓	✓	✓
Reestablishing Naturally Functioning Dunes on Developed Coasts	Journal article	2000	Karl Nordstrom, Reinhard Lampe, and Lisa Vandemark	East Coast	The authors discuss how the built environment of the coast interacts with dunes. Additional topics covered include increasing dune longevity, site selection, spatial arrangement of dunes, and protecting target species.	✓	—	—	✓
Hawai'i Dune Restoration Manual	Guidebook	2022	University of Hawai'i Sea Grant College Program	Designed for Hawai'i but most of the information is more broadly applicable.	This guide covers all the main facets of dune restoration, including invasive species removal, constructing boardwalks, and rebuilding dunes. The authors also include a troubleshooting section, monitoring advice, and information about the relationship between dune restoration and beach nourishment.	✓	✓	✓	✓

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Dune Manual	Guidebook	2016	New Jersey Sea Grant Consortium	East Coast	Covering dune ecology and engineering, this guide gives specific instructions for restoring both front and back dune ecosystems. Additional topics covered include season variability, dune breaches, Federal Emergency Management Agency (FEMA) dune standards, and invasive species.	✓	✓	—	—

GRAY INFRASTRUCTURE ALTERNATIVES

Dune restoration can be an alternative to several gray infrastructure approaches designed to reduce coastal properties' risk of flooding and erosion: bulkheads, riprap/revetments, seawalls, groins, and artificial breakwaters. The ability of a dune 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 dune restoration. See the gray infrastructure alternative tables in Section 1 for a comparison of dune restoration to these alternatives.

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Storm protection:** During severe storms, dune vegetation can reduce wind speeds, attenuate waves, and lessen the wind-driven erosion of sediment. Dune vegetation develops extensive root systems; this underground biomass is critical to maintaining the dune under pressure. Eroded dunes are more likely to experience overwash, whereas waves generally collide with and do not overtop intact dunes (Bryant et al. 2019).

- **Reduced flooding:** Dunes are highly effective at repelling coastal floodwaters. While the magnitude of this benefit may depend on the height and width of the dune field and its proximity to the ocean, strong vegetation can preserve a dune during storm surges. Dunes can dissipate floodwater energy and thus protect landward properties (Fernández-Montblanc et al. 2020).
- **Sea level rise adaptation and resilience:** While dunes cannot stop sea level rise, they are able to better prepare coasts to withstand it. Dunes can catch sand from the wind, building up dune height and width and fostering accretion. The increased elevation adds further protection (Aerts et al. 2018). Dunes are also highly mobile, allowing them to migrate landward as sea level rise intensifies.
- **Carbon storage and sequestration:** While dune ecosystems do not store as much carbon as other ecosystems, they still have a role to play in combatting climate change (Jones et al. 2008). Dune ecosystems can rapidly sequester carbon because of their nature as an early succession ecosystem. Dune soils have a high concentration of carbonate, storing carbon in the sand. Heavily vegetated dunes store more carbon than barren ones, an important consideration for management.

Social and Economic

- **Property and infrastructure protection**: Higher dunes protect inland properties and infrastructure from erosion, flooding, sea level rise, and extreme storms. Unlike many gray infrastructure approaches that accelerate erosion in adjacent areas, dune restoration provides the same protection without the erosion risk (Komar and Allan 2010). Many dune restoration projects are designed to buffer infrastructure, such as coastal highways. Dunes were successful at limiting damage to infrastructure even in extreme weather conditions, such as Hurricane Sandy in 2013 (USACE 2013).
- **Reduced erosion:** Restored dunes are effective at reducing beach erosion. Dune vegetation forms a symbiotic relationship with mycorrhizal fungi, which helps the plant develop strong roots that reduce erosion. Dunes also prevent water from reaching areas further upland, limiting erosion there (Sigren et al. 2014).
- **Increased property values:** Dune restoration reduces erosion, protecting coastal properties and thus increasing their value. However, complaints that higher dunes block beach views lead some to argue that dune restoration does not increase property values (Olander et al. 2021). As awareness increases about the benefits of nature-based solutions (NBS), it is likely that dune restoration will result in an increase in property value (Mutlu et al. 2023).
- **Reduced or avoided costs:** Dune restoration projects can help adjacent property owners save money on their flood insurance through FEMA's Community Rating System (CRS) program. The CRS rating system rewards communities that complete projects to reduce flood risk, including dune restoration. This incentive often helps generate public support for dune restoration projects (Young and Clark 2015). Dunes can also trap and store sand, allowing them to supply sand to eroded beaches in the future. This is especially important as hardened coasts disrupt natural sediment transport processes. Dunes can serve as a sand bank and reduce the need for nearby beach nourishment projects (Hoonhout and de Vries 2019).

- **Jobs:** Contractors will need to be hired to perform the restoration activities, boosting the local economy.
- **Mental health and well-being:** Dune restoration preserves access to intact beaches, improving residents' mental health and psychological well-being.
- **Cultural values:** Dunes are valuable cultural resources, inspiring art and spiritual values (Richardson and Nicholls 2021).

Ecological

- **Enhanced biodiversity:** Beach berms and groomed beaches generally have low levels of biodiversity because of the lack of shelter and high levels of human disturbance on the open beach. Replacing an open beach with a vegetated dune can significantly restore biodiversity by reintroducing habitat (Johnston et al. 2023). Furthermore, invasive species removal as a part of restoration can also enhance biodiversity. Planting a diverse set of species allows for more interspecific interactions to occur, luring additional species to the site (Pickart 2021).
- **Increased primary productivity:** Planting vegetation on a dune spurs rapid growth, which boosts primary productivity. Once the original plants become established, more plants will naturally colonize the dunes and increase the overall biomass of the ecosystem (Sigren et al.2014).
- **Reduced runoff:** Dunes receive a large amount of surface water, both from tidal exchanges and overland runoff. Dunes facilitate the infiltration of surface water back into the ground, reducing runoff (Bridges et al. 2015).

BARRIERS AND SOLUTIONS FOR PRACTITIONERS

Common Barriers

Several barriers are common across many of the NBS strategies; these are described in more detail in Section 1 of the Roadmap. Additional notes about the barriers specific to dune restoration are included here.

- **Expense:** As sea levels continue to rise, the beach and dune ecosystems must either move inland to survive or be submerged. Often, high-priced coastal real estate is located directly inland of dunes, generating significant opposition to moving or restoring dunes. Past managed retreat initiatives have achieved only limited success in acquiring coastal properties because of high costs (Vandemark 2000).
- **Capacity**
- **Public opinion**
- **Conflict with other land uses:** Beach grooming prevents dunes from forming by eliminating topographic changes in the beach, reducing wrack and inhibiting vegetation growth (Dugan and Hubbard 2010). However, beach grooming is essential to attracting tourists to a beach, with many visitors desiring a certain beach aesthetic

not compatible with dune restoration (Nordstrom et al. 2000). Finding compromises to restrict beach grooming around restoration sites is critical to a successful project (Johnston et al. 2023).

- Regulation
- Lack of effectiveness data

Economic

- **Cost of sediment:** Sediment used to restore a dune needs to be compatible with the natural beach sand in terms of grain size and color. However, sediments that meet these criteria may not be located nearby, adding high transportation costs to the project. Sediment is a nonrenewable and highly valuable resource, making it difficult to procure (Palaparthi et al. 2022). Furthermore, dune restoration projects often compete with beach nourishment projects for the same sediment sources. Collaborating with already-planned dredging projects for a beneficial use of dredged material is a way to overcome this barrier (USACE n.d.).

Community

- **View obstruction:** There are numerous lawsuits claiming that dune restoration projects have obstructed the view from an oceanfront property. While higher dunes protect these properties, they also block scenic ocean views, which angers some property owners (Olander et al. 2021).
- **Construction disruption:** Construction on dunes may impact access to nearby beaches for recreation. This will impact the local economy which is often highly dependent on tourism revenue. To mitigate this disruption, construction could be scheduled for the offseason when fewer visitors are present (Olander et al. 2021).
- **Off-road vehicle (ORV) use:** ORVs have deleterious impacts on dune health, with ORV tracks causing dune degradation. Studies have shown that ORV use causes a decline in native species and species richness, opening the door to invasive species to recolonize the dune (Hogan and Brown 2021). ORVs should be prohibited from the restoration site to increase the likelihood of a successful project.
- **Limited beach access:** Beach access paths create gaps in the dunes, increasing the risk for overwash and dune erosion during severe storms. Sand paths have a greater impact on dunes than wooden boardwalks (Purvis et al. 2015). However, financial constraints mean that wooden boardwalks can only be built in a limited number of locations, reducing beach access.
- **Temporary increase in flood risk:** While invasive species are detrimental to the ecology of dunes, they are effective at anchoring sediment. Invasive species allow dunes to grow in height and stability, reducing erosion and increasing coastal flood protection. When invasive species are removed as part of a dune restoration project, their ability to repel floods ceases as well. Once established, native plants will have the same coastal defense properties, but it may take a few years before the vegetation cover reaches its previous extent (Biel et al. 2017).

Ecological

- **Different morphology than natural dunes:** Restored dunes are generally smaller and more linear than natural dunes. Restored dunes also exhibit lower species diversity than natural dunes. This means that the benefits of dune restoration may be less impactful than conserving natural dunes (Nordstrom et al. 2000).
- **Degradation of sediment source habitat:** Sediment for dune restoration is generally extracted via dredging from the bottom of a channel. This process has many negative environmental impacts, including increasing suspended sediments, turbidity, and siltation rates. Excess sediment in the water disrupts the ecology of coral reefs, seagrasses, and estuaries, contributing to their decline (van Maren et al. 2015).
- **Drought:** In arid regions, dune plants often struggle to establish due to a lack of rainfall. Therefore, most dune restoration projects are limited to areas that receive more rainfall or require irrigation to help the plants survive. Another solution to increase plant survival is to use jellyfish biomass as fertilizer, partnering with local invasive jellyfish removal projects (Emadodin et al. 2020).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Santa Monica Beach Restoration Pilot Project	Santa Monica, CA	The Bay Foundation, City of Santa Monica, California Department of Parks and Recreation, University of California Santa Barbara	Installed sand fencing, planted native plants, and ceased beach grooming	3 acre	300,000	Not provided	On a heavily groomed urban beach, workers used sand fences and native plants to create a small dune complex. The site was used as a breeding ground for the endangered western snowy plover (*Charadrius nivosus nivosus*).	Sea level rise, increased storm severity	The project was well-received by the community and an additional 5 ac of dune will be restored nearby.
Cape Lookout Dune Restoration Project	Cape Lookout State Park, OR	**US Geological Survey,** Oregon State Parks, Oregon State University, Oregon Department of Geology and Mineral Industries	Cobbled berm construction, increasing dune elevation with geotextile bags, sand nourishment, installing native plants	1 acres	125,000	4 months	Workers constructed a cobbled berm and artificial dunes to help protect a nearby campground and road. The dunes were made of geotextile bags and sand and stabilized with native plants.	Sea level rise, severe storms, coastal flooding	Extreme waves overtopped the entire length of the dune, inflicting minor damage on the structure. To prevent this from happening again, the dunes will be elevated and potentially moved further inland.

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Flagler Beach Dune Restoration Project	Flagler County, FL	US Army Corps of Engineers, Flagler County	Sand nourishment, installing native plants	2.6 linear mi	35 million	6 years (ongoing)	After Hurricane Matthew destroyed the natural dunes and a major coastal highway, leaders decided a dune restoration project was needed. Additional sand is being placed on the dunes, which will then be covered by native plants.	Sea level rise, severe storms, coastal flooding	The project has encountered numerous setbacks, including operations being disrupted by successive storms and ballooning costs. The elongated project timeline is a result of work stoppages during sea turtle nesting season.
Abbots Lagoon Coastal Dune Restoration Project	Point Reyes National Seashore, CA	**National Park Service**	Mechanical removal of invasive European beachgrass (*Ammophila arenaria*) and ice plant (*Carpobrotus* spp.)	120 acres	3.24 million	7 months	Contractors mechanically removed the invasive species by burying them 6 to 9 ft under the sand. After the invasive species were removed, native plants recolonized the dune.	Sea level rise	After restoration was completed, invasive species still recolonized some areas. These plants were then treated with herbicide and mowed.
Duxbury Beach Crossover 1&2 Dune Restoration Project	Duxbury, MA	Duxbury Beach Reservation, Inc., Woods Hole Oceanographic Institute	Sand fencing, sand nourishment, planting native species	38 acres	1.4 million	4 months	Contractors built up the dune by transporting sand quarried inland via truck to the site. Next, sand fences were installed, and native vegetation was planted, including American beachgrass (*Ammophila breviligulata*).	Coastal flooding, severe storms	The project was scheduled to avoid disturbing nesting seasons for shorebirds.

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
McFaddin Beach and Dune Restoration Project	McFaddin National Wildlife Reserve, TX	**US Fish and Wildlife Service,** National Oceanic and Atmospheric Administration, Texas Commission of Environmental Quality, Texas General Land Office, Texas Parks & Wildlife Department	Sand nourishment, planting native vegetation	17 linear mi	87 million	16 months (ongoing)	Sand is being dredged offshore and piped to the restoration site. After the sand is graded, then contractors will plant native vegetation. The project will protect the valuable salt marsh ecosystem that lies behind the dune.	Coastal flooding, sea level rise, increasingly severe storms	A smaller 2017 pilot project helped planners hone the best restoration strategies for this immense project.

Bolding indicates DOI affiliates.

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Coastal Habitats
6. Living Shoreline Creation

DEFINITION

Living shoreline creation refers to the process of planting vegetation along the shoreline and installing structures that help hold the vegetation in place (Olander et al. 2021). Living shorelines help prevent erosion along the shoreline, providing an alternative to traditional gray infrastructure like bulkheads, ripraps, or jetties (Figure 1). These hardened shorelines are on the rise as American coastal regions rapidly urbanize, with one-third of American coastlines expected to be hardened by 2100. Living shorelines are often preferred to gray infrastructure because of their ability to trap sediments from tidal waters, allowing them to gain elevation as sea levels rise (NOAA 2023). Most living shorelines include a breakwater composed of bagged oyster shells, granite, eco-friendly concrete, or reef balls (Olander et al. 2021). Living shoreline creation typically involves planting vegetation, installing organic material, constructing oyster reefs or living breakwaters, and adding sills or other holding structures (NOAA n.d.).

TECHNICAL APPROACH

Living shoreline creation typically connotes softer or greener shorelines as opposed to gray or hard shorelines (Sutton-Grier et al. 2018). However, many living shoreline projects implement a hybrid of green and gray infrastructure (NOAA n.d.). The following approaches to living shoreline creation encompass both green-gray hybrid strategies and completely green shorelines:

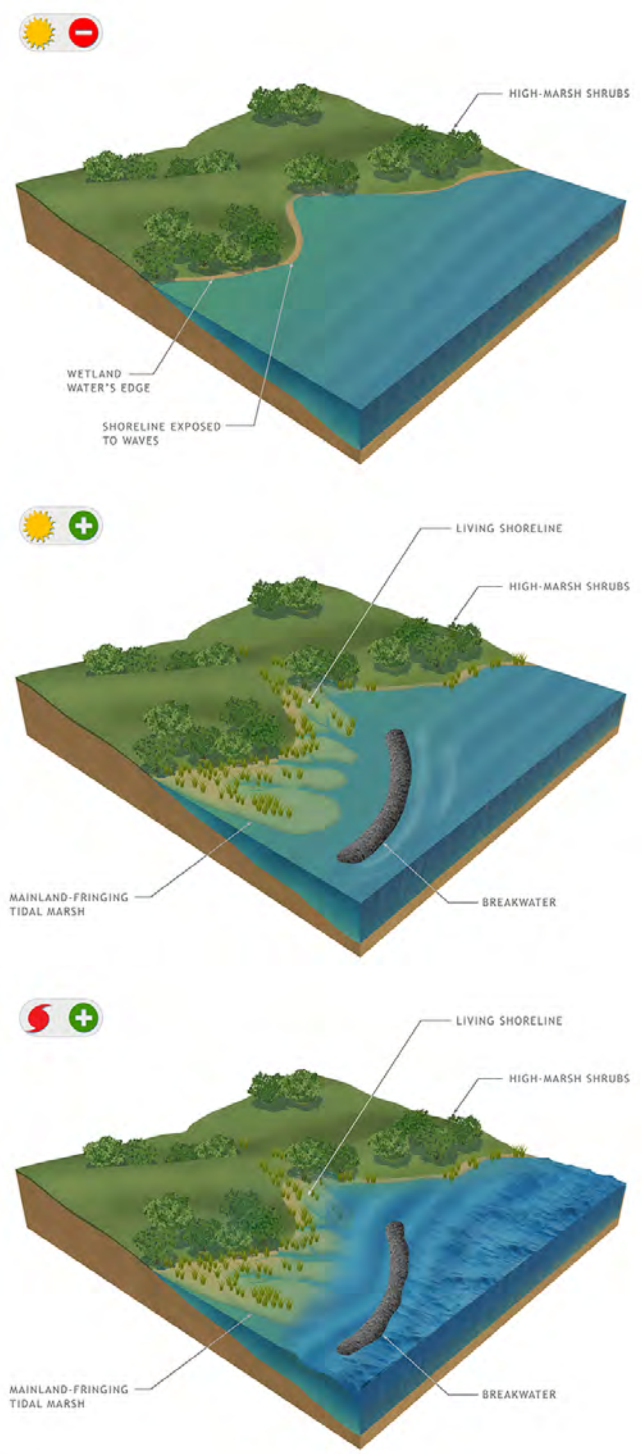
1. **Removing gray coastal barriers:** Before creating a living shoreline, any existing coastal protection structure must be removed. Removing bulkheads, riprap, and revetment must be done in a way that wave energy is dissipated during the removal process. This ensures that workers can safely access the site and the new living shoreline can get established under lower wave energy conditions. Dispersing wave energy generally entails constructing temporary breakwaters that will shield the site during construction (FWC n.d.).

2. **Creating the living shoreline structure:**

    - **Organic materials:** Bio logs, organic fiber mats, and seeded coir logs are some examples of materials used for living shoreline structures. These materials are all biodegradable and mimic natural shoreline ecology, providing habitat for intertidal species that need shelter and helping vegetate the shoreline (Elgin 2022). Furthermore, these materials can serve as living breakwaters which dissipate wave energy as it reaches the shore (NOAA n.d.).

    - **Oyster reefs:** Oyster reefs help protect the coast, stabilizing the seafloor and attenuating waves before they hit the shore. Oyster reef restoration techniques

Figure 6.1 Unprotected shoreline, then shown with a living shoreline under sunny conditions and storm conditions



Note: The living shoreline provides protection from erosion and facilitates marsh growth, leading to additional coastal protection.

Illustration courtesy US Army Corps of Engineers include distributing large amounts of shells with high-pressure hoses, constructing a linear reef to stabilize the shoreline, and bagging oyster shells to jump-start a reef (Figure 2; NOAA 2022).

- **Living breakwaters:** *Living breakwaters* is a broad term that combines many of the other living shoreline creation techniques into a fabricated coastal defense structure. A *breakwater* is a rubble mound structure created in the intertidal region just offshore. Breakwaters are then enhanced with oyster reefs and other organic materials to mimic natural ecology (GOSR 2020).
- **Sills and other holding structures:** A *sill* is a low stone structure that runs parallel to the existing shoreline (VIMS n.d.). Sills help stabilize vegetation in high wave energy environments (NOAA n.d.).
- **Reef balls:** *Reef balls* are small artificial reefs that are meant to mimic natural reef systems (RBF 1999). Reef balls help create living breakwaters and provide enhanced protection to the coast (Olander et al. 2021).
- **Eco-friendly concrete:** *Eco-friendly concrete* is a special type of concrete that is designed specifically for shoreline strengthening and working in tandem with natural barriers. Eco-concrete can help stabilize a living breakwater or serve as a holding structure to support vegetation (Smith et al. 2020).

Figure 6.2 Aerial view of living shoreline construction using oyster castles

Photo courtesy US Fish and Wildlife Service Northeast Region

3. **Revegetation:** Once the structural components of the living shoreline have been installed, revegetation can occur. Revegetation involves planting riparian, marsh and submerged aquatic vegetation, which helps reduce shoreline erosion (NOAA n.d.). On sites where there is low-to-moderate erosion, direct planting can occur. However, in areas where there is severe erosion, one of the following planting techniques should be implemented:

    - **Live staking:** Live staking involves taking cuttings of woody plants and driving them into the shoreline substrate. The cuttings will eventually form roots and begin to grow (NYS DEC n.d.).
    - **Contour wattling:** Working in tandem with live staking, *contour wattling* refers to laying bundles of branches in between the wood stakes and covering them with soil. The branches will stabilize the shoreline and grow (NYS DEC n.d.).
    - **Brush matting:** Similar to contour wattling, brush matting is the process of covering a shoreline with branches to stimulate growth. This simple strategy can reduce wave energy by up to 60% (Herbert et al. 2018).
    - **Vegetated riprap:** This green-gray hybrid approach involves inserting live stakes in between the rocks of riprap. This helps add vegetation to the shoreline without losing the erosion protection provided by the riprap (NYS DEC n.d.).

OPERATIONS AND MAINTENANCE

Living shorelines require regular invasive species and debris removal as well as occasional vegetation replanting or sand fill additions to keep organic materials in place. The estimated cost of maintaining a living shoreline is about $100 per linear foot per year (NOAA 2015).

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Low-to-moderate wave energy:** Vegetation in living shorelines cannot tolerate high wave energy conditions. Areas with low-to-moderate wave energy allow for vegetation to become established and provide ideal conditions for intertidal ecosystems (Zylberman 2016).
- ✓ **Fetch exposure of between 1 and 5 mi:** *Fetch* is the length over water that wind blows without any obstruction. Fetch influences the type of waves that hit the shore, with a higher fetch corresponding to larger waves. Having the appropriate amount of fetch ensures that living shorelines will be able to handle storm surges (Berman and Rudnicky 2008).
- ✓ **Low-to-moderate erosion:** While living shorelines are often installed to remediate erosion, a site with severe erosion is not suitable for a living shoreline. Living shorelines cannot alter external factors influencing erosion, meaning that erosion still may occur even if vegetation is planted. However, if the cause of erosion is determined to be hard armoring, then replacing the hard structure with a living shoreline is likely to reduce erosion (Zylberman 2016).

- ✓ **Near a tidal marsh:** Living shorelines are effective at working in tandem with tidal marshes to control coastal hydrology. Marshes also thrive in similar conditions to living shorelines, making them a proxy for success (Zylberman 2016).
- ✓ **Shallow bathymetry:** A site with a shallow bathymetry is recommended for living shoreline projects because these conditions are conducive to intertidal ecosystems. If there is a steep drop-off in depth near the shoreline, then the wave regime and sediment transport will be significantly altered. A 1 m contour line greater than 30 m from the shoreline is recommended for living shoreline projects (Miller et al. 2015).
- ✗ **Frequently covered by thick ice:** Thick ice can cause significant damage to a living shoreline. As ice becomes frozen to the vegetation, buoyant forces related to the fluctuation in tides can negatively affect the structural integrity of the shoreline (Miller et al. 2015).
- ✗ **Infrastructure, such as buildings or roads, adjacent to the shoreline:** One of the benefits of living shorelines is that they dissipate wave energy over a longer area than hardened shorelines. However, if there is infrastructure directly along the coast, then there will not be enough space to install a properly functioning living shoreline (Carey 2013).
- ✗ **Adjacent to a seawall that will not be removed:** Seawalls disrupt natural sedimentation processes, which result in a lack of sediment downdrift. As a result, areas directly adjacent to a seawall often experience high levels of erosion. If a living shoreline is starved of sediment, then its ability to fight erosion is compromised (Zylberman 2016).
- ✗ **Extreme water depths:** Deep waters near the shoreline encourage boats to go near the living shoreline, potentially damaging the underwater portion. Furthermore, many aquatic plants cannot tolerate deep water (MDE 2013).
- ✗ **Located on a narrow waterway:** Living shorelines take up more space than traditional hard shoreline armoring. A narrow waterway may not have the space to accommodate both the underwater and terrestrial portions of a living shoreline (MDE 2013).

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?
Natural and Structural Methods for Shoreline Stabilization	Document	2015	National Oceanic and Atmospheric Administration (NOAA), US Army Corps of Engineers (USACE)	National	Developed by NOAA, this resource helps users determine the best living shoreline design based on the specific attributes of the site. The guide contains a helpful infographic that displays the spectrum of gray to green shoreline infrastructure.	✓	✓	—	—
Guidance for Considering the Use of Living Shorelines	Guidebook	2015	NOAA	National	Also developed by NOAA, this guidebook outlines the physical, ecological, and policy considerations that influence a living shoreline creation project. Emphasis is given to the site suitability factors for successful projects.	✓	✓	—	—
NOAA's Living Shoreline Projects	Story map	2023	NOAA	National	Containing 199 case studies of successful living shoreline creation projects, this story map documents a variety of restoration strategies from across the country. The map displays the location of each project and gives a short description of the techniques used at that site.	—	—	—	✓
Living Shorelines Training for Marine Contractors	Guidebook	2019	Florida Fish and Wildlife Conservation Commission	Florida but most of the information is more broadly applicable	This guide encompasses the technical aspects of implementing and maintaining living shoreline creation projects. The authors provide in-depth design guidelines and information about the permitting process.	✓	✓	✓	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Shoreline Protection	Website	2023	Michigan Department of Environment, Great Lakes and Energy	Great Lakes region	Discussing the trade-offs between living and hard shorelines is the primary focus of this resource. The website contains best management practices, fact sheets, and a story map illustrating successful projects in the Great Lakes region.	✓	—	—	✓
Living Shorelines Engineering Guidelines	Document	2016	Stevens Institute of Technology	National	This technical document delves into the hydrodynamic, terrestrial, and ecological parameters that impact living shoreline creation projects. Additional topics include regulatory considerations and invasive species management.	✓	✓	✓	—
Living Shorelines and Nature-Based Solutions Guidebook	Guidebook	2022	Commonwealth of the Northern Mariana Islands' Bureau of Environmental and Coastal Quality	Designed for the Northern Mariana Islands but most of the information is more broadly applicable.	Viewing living shorelines through the nature-based solutions paradigm, this guidebook provides techniques to create living shorelines. The guidebook contains additional information about the permitting steps and funding opportunities available.	✓	✓	—	—
A Guide to Living Shorelines in Texas	Guidebook	2020	Texas Coastal Management Program	Texas but most of the information is more broadly applicable.	This resource provides an easy seven-step guide to living shoreline creation projects as well as cost projections, planting guides and permitting considerations. Furthermore, the guide explores hybrid shoreline stabilization methods and recommends techniques based on a property's characteristics.	✓	✓	—	✓

GRAY INFRASTRUCTURE ALTERNATIVES

Living shorelines can be an alternative to gray infrastructure approaches that address coastal erosion and flooding: bulkheads, riprap/revetments, seawalls, groins, and breakwaters. The ability of a living shoreline project to replace or supplement these gray infrastructure approach 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 a living shoreline. See the gray infrastructure alternative tables in Section 1 for a comparison of living shorelines to these alternatives.

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Reduced flooding:** Living shorelines have been shown to reduce flood risk because of their ability to repel water from developed areas, attenuate wave energy, and reduce erosion once waves reach the shore. Unlike hardened shorelines, living shorelines employ more flexible water management strategies, allowing incoming waves to gradually dissipate over a longer surface area (Moosavi 2017). While gray infrastructure can also mitigate coastal flooding, it is often vulnerable to being breached by large waves and has more expensive maintenance costs (Waryszak et al. 2021).

- **Storm protection**: Living shorelines are more effective at protecting coastal communities from hurricanes than hardened shorelines or natural marshes. This is because living shorelines have higher densities of vegetation than natural marshes or traditional bulkheads, allowing the shoreline to maintain its elevation (Smith et al. 2020).

- **Sea level rise adaptation and resilience:** Living shorelines can gain elevation with sea level rise. However, this depends on numerous factors, including the rate of sediment accretion, management practices and nearby land uses (Mitchell and Bilkovic 2019). Adding biotic components to a living shoreline like oyster shells creates a dynamic structure that can better adapt to rising sea levels (Risinger et al. 2017).

Social and Economic

- **Reduced erosion:** Living shorelines protect coasts from erosion by allowing native plants to stabilize sand and soil with their dense web of roots. Living shorelines promote the accretion of sediments, which provides more substrate to bolster eroding shorelines (Polk and Eulie 2018). Living shorelines also reduce scour, where sediment is removed from the bank of a waterbody, which hardened shorelines like bulkheads exacerbate (Herbert et al. 2018).

- **Property and infrastructure protection:** Despite being low-lying compared to traditional bulkheads, living shorelines are effective at mitigating storm surges. This is because of the greater distance between the ocean and nearby development that living shorelines provide, restoring the natural intertidal exchanges. Vegetation still has a high wave attenuation capacity even while submerged, preventing water from reaching properties and infrastructure further inland (Polk et al. 2022).

- **Recreational opportunities:** Living shorelines can boost recreation by increasing water quality and local fish stocks, which helps attract recreational fishermen (Olander et al. 2021).
- **Mental health and well-being:** Living shorelines help preserve greenspace for the public to enjoy along the coast, improving mental health and psychological well-being.
- **Jobs:** Contractors will need to be hired to create a living shoreline, aiding the local economy.
- **Resilient fisheries:** Reef balls, living breakwaters, and oyster reefs created during living shoreline projects increase habitat for both finfish and shellfish, sustaining fish populations. This helps increase the total output of the local fishing industry (Olander et al. 2021).
- **Food security:** Some coastal residents rely on healthy fish stocks for their own nutrition, meaning that living shorelines aid local food security (Olander et al. 2021).
- **Cultural values:** Living shorelines can help educate residents about local ecology and provide ideal locations for environmental education.

Ecological

- **Improved water quality:** Living shorelines create a buffer in between anthropogenic terrestrial environments, the source of nutrient and sediment pollution, and the waterbody (Erdle et al. 2006; Askvig et al. 2011). Living shorelines help facilitate denitrification, a process that removes nitrogen from the soil, thus precluding it from entering the water. This reduces nutrient levels in surrounding waterbodies, mitigating one of the major drivers of eutrophication. Along with eutrophication, algae blooms and hypoxic zones decrease when living shorelines are installed (Onorevole et al.2018). Living shorelines also provide habitat for oysters, which filter excess pollutants out of the water (Askvig et al. 2011).
- **Enhanced biodiversity:** Living shorelines have been found to increase biodiversity for both intertidal and marine ecosystems, including higher and more diverse fish populations (Currin 2019). Studies show that fish, crab, and shrimp populations in created living shorelines match those of natural shorelines within three years of construction (Currin et al. 2007).
- **Invasive and nuisance species management:** Hardened shorelines eliminate vital spawning and feeding habitats for native species and better suit the capabilities of invasive species, helping them proliferate (EGLE 2023). Using living shorelines instead of bulkheads or riprap reduces opportunities for invasive species.

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 these barriers specific to living shoreline creation are included here.

- **Expense**
- **Capacity**
- **Public opinion:** Many coastal communities have misconceptions about the effectiveness of living shorelines and falsely believe that bulkheads provide a greater degree of protection from coastal flooding. This is largely a result of the ubiquity of hardened shorelines along developed coasts and widespread unfamiliarity with living shorelines (Scyphers et al. 2020).
- **Conflict with other land uses:** While living shorelines increase values of coastal properties, they require that structures be somewhat removed from the coast. Hardened shorelines allow for piers, boardwalks, and residences to be built directly on the water whereas living shorelines are designed to give space in between the water and anthropogenic infrastructure. This protects coastal communities in the long run but limits the economic activity of structures that need to be directly on the water in the short run.
- **Regulation:** Many living shoreline projects will require multiple permits to be approved before construction can begin. At the federal level, the projects will require a permit issued by the USACE. At the state level, permitting requirements differ from state to state, but many states have much narrower parameters than the USACE. At the local level, land use authorities have their own set of criteria needed to approve a project. Navigating the triple-tiered permitting system adds another layer of unpredictability to living shoreline restoration projects (RAE 2014).
- **Lack of effectiveness data**

Economic

- **Cost uncertainty:** Because of the variability of coastal environments, it is difficult to estimate the cost of a living shoreline creation project. While living shorelines typically cost less than bulkheads, the cost uncertainty of living shorelines sometimes causes communities to choose hardened structures instead (RAE 2014).
- **High cost of land:** Living shorelines take up more land than hardened coastal defenses, which can result in nearby structures being removed. This is called *managed realignment* (Neal et al. 2017). Coastal properties are significantly more expensive than analogous inland ones, resulting in a high cost for buyouts (Rinehart and Pompe 1999).

Community

- **Limited shoreline access:** Vegetation on living shorelines cannot endure heavy foot traffic, meaning that many areas must be closed for public recreation. Many states require that areas below the high or low tide line be publicly accessible, termed *public trust shoreline*. While living shorelines may alter some beach access points, they are better at preserving shoreline access in the long term than bulkheads (NOAA 2015).

Ecological

- **Invasive species:** Living shorelines are vulnerable to invasive species, similar to many other intertidal habitats. While living shorelines are more resilient to invasive species than hardened shorelines, control mechanisms may still need to be implemented (Hacker et al. 2001).
- **Trade-offs between existing habitat and created living shorelines:** When a living shoreline is created in an area that was previously undeveloped, some of the previous ecological functions may not be retained. Living shoreline creation may involve converting unvegetated wetlands and shallow subtidal zones into a marsh bounded by a sill. While the living wetland creates a greater diversity of habitats, disruptions to the original habitat will occur (Bilkovic and Mitchell 2013).
- **Limited resilience in hardened environment:** If small living shoreline creation projects are surrounded by hardened shorelines, then the ecological and

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size, linear ft	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Fog Point Living Shoreline Project	Glenn Martin National Wildlife Refuge, MD	**US Fish and Wildlife Service (USFWS)**	Living breakwaters, sills	20,950	9 million	1 year	To protect a vulnerable marshland, protective sand and rock structures will be built to rejuvenate an eroding shoreline. This shoreline then was buttressed by submerged aquatic vegetation and clam beds.	Increased storm severity, coastal flooding	Used articulated dump trucks to reach shallow areas that weren't accessible to barges.
Gandys Beach Living Shoreline	Gandys Beach Preserve, NJ	**USFWS,** The Nature Conservancy (TNC), Rutgers University, Stevens Institute of Technology	Living breakwaters, oyster reef restoration	2,750	880,000	2 years	To create a living breakwater, managers installed oyster castles and bags of clam and oyster shells. This also helped restore the oyster reefs along the shoreline.	Increased storm severity	Four years after the restoration was complete, erosion was still occurring along the shoreline. Workers realigned the breakwaters into smaller structures, solving the problem.
Jamaica Bay Living Shoreline Project	Gateway National Recreation Area, NY	**National Park Service,** Fund for the City of New York	Bagged oyster shells, oyster reef restoration, biodegradable coir logs, live staking	2,400	4 million	5 months	The project team added sand to raise the surrounding wetland, revegetated the shoreline, added organic material, and created an oyster reef using bagged oyster shells.	Increased storm severity, coastal flooding	It is important to manage the spectrum of saltwater- to freshwater-tolerant plants, as this project was meant to return a marsh to freshwater state after it turned brackish.

Name and Link	Location	Leading Organizations	Techniques Used	Size, linear ft	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Shinnecock Living Shoreline Restoration Project	Long Island, NY	Shinnecock Indian Nation, **US Geological Survey (USGS),** Cornell University	Oyster reef restoration, revegetation	3,000	3.75 million	1 year	Team members dredged additional sand onto the beach, plant native vegetation, added stones to support the vegetation, and created oyster shells via calcification.	Increased storm severity, sea level rise, coastal flooding	Oyster larvae often need to be induced to attach onto the shells provided.
Weaverling Spit Beach Living Shoreline Project	San Juan Islands, WA	Samish Indian Nation	Installing organic materials, revegetation	1,400	N/A	N/A	To reduce shoreline erosion, workers added driftwood, pebbles, and native vegetation, mimicking a natural shoreline in the Pacific Northwest.	Increased storm severity, coastal flooding	Even heavy driftwood must be anchored into the shoreline to keep it from washing away during severe storms.
Jupiter Inlet Living Shoreline Project	Jupiter Inlet Lighthouse Outstanding Natural Area, FL	**Bureau of Land Management,** Jupiter Inlet District	Living breakwaters, revegetation	550	540,000	4 months	Contractors built a living breakwater that combined green and gray elements and revegetated the shoreline to reduce erosion.	Increased storm severity, coastal flooding, sea level rise	Diversified plantings based on proximity to mean high water levels.
San Francisco Bay Living Shorelines Project	San Rafael, CA	**USGS,** TNC, California State Coastal Conservancy, NOAA	Reef balls, living breakwaters, eco-friendly concrete, oyster reef restoration, eel grass restoration	1,300	2.1 million	2 months	To enhance wave attenuation, workers placed reef balls, eco-friendly concrete, and oyster shells to restore an oyster reef that will also serve as a living breakwater. Eel grass was then transplanted to the surrounding areas.	Coastal flooding	Adequate space between oyster reefs, and eel grass is necessary because of competition for space.

Name and Link	Location	Leading Organizations	Techniques Used	Size, linear ft	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Swift Tract Living Shoreline Restoration	Baldwin County, AL	TNC, Alabama Department of Conservation and Natural Resources, National Fish and Wildlife Foundation, NOAA	Living breakwaters, oyster reef restoration, revegetation	2,100	549,341	1 year	To mitigate shoreline erosion, a gabion and oyster shells were placed offshore to form a living breakwater. The shoreline was also revegetated.	Increased storm severity	Because of the low salinity of the project site, the oyster reef attracted less oysters and more mussels than managers hoped for.

Bolding indicates DOI affiliates.

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Coastal Habitats
7. Mangrove Restoration

DEFINITION

Mangrove ecosystems are a form of coastal wetlands found in tropical and subtropical regions. These systems support halophytic (salt-loving) trees, shrubs, and other plants, and are dominated by mangrove trees. In the continental United States there are three mangrove tree species: red mangrove (*Rhizophora mangle*), which grows along the shoreline where conditions are harshest and is easily recognized by its arching prop roots; black mangrove (*Avicennia* sp.), which often grows more inland and at higher elevation than red mangrove and has root projections called *pneumatophores* to supply the plant with air in submerged soils; and White Mangroves (*Laguncularia racemosa*), which often grow inland with no outstanding root structures. (EPA 2022; Shepard et al. 2022). Restoring degraded or destroyed mangrove systems typically involves restoring natural hydrology and, in some cases, planting mangrove trees.

TECHNICAL APPROACH

While mangrove site restoration techniques vary, the following steps are generally used to restore the site's structure and function to a more natural state:

1. **Hydrological restoration:** Restoring mangrove systems revolves around restoring the natural hydrology of the site. Hydrological restoration techniques will differ based on the site, but can involve interventions like clearing and restoring tidal creeks, installing culverts or channels beneath roads or other structures that impede tidal flow, diverting excessive freshwater flows, and/or removing structures that have previously blocked tidal flow (Figure 1; Lewis and Brown 2014, Botero and Salzwedel 1999, Teutli-Hernández et al. 2020).
2. **Removing disturbance:** After hydrology is restored, it is important to rid the site of any factors that would potentially harm or slow the regeneration of mangroves. These steps could include actions such as removing undesired species that might outcompete mangroves, removing trash, leveling out the ground, fencing out grazing livestock, setting up protective netting, and amending soil (Lewis and Brown 2014).
3. **Revegetation:** Reestablishment of mangrove trees can occur in two primary ways:
   - **Natural regeneration (also called *passive restoration*):** Relying on naturally dispersed mangrove propagules (seeds) to restock the degraded area (Lewis and Brown 2014, Teutli-Hernández et al. 2020).
   - **Artificial regeneration (also called *active restoration*):** Direct planting of mangrove propagules (seeds) or seedling trees that were grown in a nursery (Figure 2; Lewis and Brown 2014, Teutli-Hernández et al. 2020).

Figure 7.1 Hydrologic restoration for a mangrove forest

Photo courtesy US Army Corps of Engineers South Atlantic Division

OPERATIONS AND MAINTENANCE

After a mangrove restoration project is completed, it is important to regularly remove trash and debris that could inhibit seedling growth. If grazing occurs in the area, access to the site should be controlled to limit grazing damage. Minor hydrological repairs may be needed over time to maintain tidal flows, and new mangrove seedlings or propagules may need to be planted as well.

FACTORS INFLUENCING SITE SUITABILITY

- ✓ Mangroves thrive in intertidal areas where soil salinity ranges from 3–27 ppt (Thorhaug 1990; Kairo et al. 2001; Kaly and Jones 1998; Smithsonian, n.d.)
- ✓ Mangroves can also grow in enclosed lagoons on inland depressions that are only periodically flushed by tides (such as Indian River Lagoon in Florida)
- ✓ Mangroves survive best in low wave energy areas (Teas 2009)
- ✗ Mangroves do not survive well in areas where there is frost or extended cold periods; however, their range is shifting northward in the United States because of climate change (Shepard et al. 2022)

Figure 7.2 Red mangrove seedling

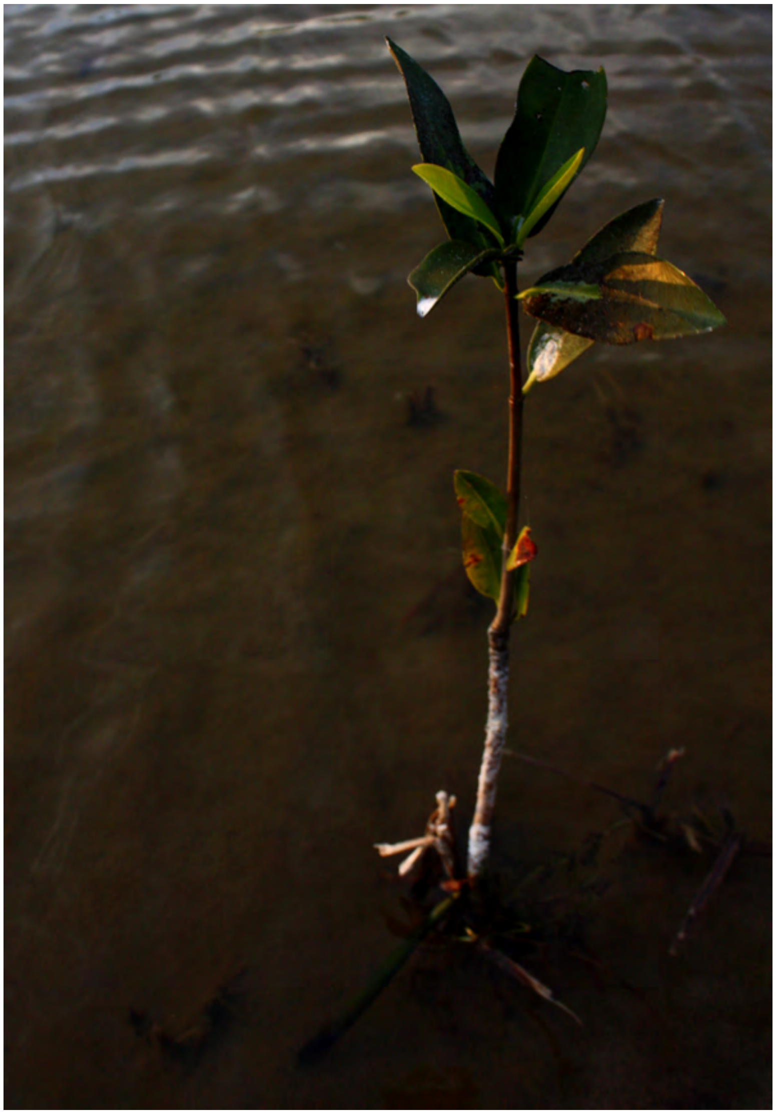

Photo courtesy Big Cypress National Preserve

TOOLS, TRAINING, AND RESOURCES FOR PLANNING AND IMPLEMENTATION

						Resource Includes			
Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Ecological Mangrove Rehabilitation	Guidebook	2014	Roy R "Robin" Lewis III & Ben Brown	Global	Detailed guide describing the types of assessment needed to determine the best plan for mangrove restoration. Also includes implementation guidance.	✓	—	✓	✓
Ensuring a Future with Mangroves	Guidebook	2022	The Nature Conservancy	Gulf of Mexico	Handbook for coastal communities and public agencies that can inform the protection, management, and restoration of mangroves. Focuses primarily on high-level policy guidance.	—	—	—	✓
Mangrove Ecological Restoration Guide: Lessons Learned	Guidebook	2020	Center for International Forestry Research	Global	Detailed guide on the steps needed to plan, implement, and monitor mangrove restoration. Includes detailed site characterization as part of the planning process.	✓	—	✓	✓
The Guidelines of Mangrove Restoration for the Western Indian Ocean Region	Guidebook	2020	UN Environment Programme	Western Indian Ocean	Detailed guide on the steps needed to plan and implement mangrove restoration, plus case studies with lessons learned from projects in the Western Indian Ocean region.	✓	—	✓	✓
Mangrove Restoration Guide	Guidebook	2015	Global Nature Fund	Global	Detailed guide on community-based mangrove restoration, focused on restoring hydrological processes to facilitate natural mangrove regeneration.	✓	—	—	—

GRAY INFRASTRUCTURE ALTERNATIVES

Mangrove restoration can be an alternative to several gray infrastructure approaches that reduce the effects of shoreline erosion and coastal flooding: dikes, seawalls, and artificial breakwaters. The ability of a mangrove 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 mangrove restoration. See the gray infrastructure alternative tables in Section 1 for a comparison of mangrove restoration to these alternatives.

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Reduced flooding:** Mangroves can attenuate storm surges and their associated peak water level height and waves; therefore, they have the potential to reduce coastal flooding height and extent during storm events (Dasgupta et al. 2019; Krauss et al. 2009; Gijsman et al. 2021; Menéndez et al. 2018, 2020; Montgomery et al. 2019; Narayan et al. 2019). The extent to which mangroves can reduce flood height and area depends on differing factors such as storm and mangrove forest characteristics (Dasgupta et al. 2019; Krauss et al. 2009; Gijsman et al. 2021; Menéndez et al. 2018, 2020; Montgomery et al. 2019; Narayan et al. 2019).
- **Carbon storage and sequestration:** Mangroves systems store and sequester carbon at very high rates (Macreadie et al. 2021).
- **Sea level rise adaptation and resilience:** Mangroves can directly and indirectly contribute to soil accretion processes through production of organic material as well as retention of sediments. It is possible that, in some areas, mangroves could help reduce the impacts of sea level rise through their ability to accrete soils along the coast. However, this is dependent on many factors (Krauss et al. 2013).

Social and Economic

- **Recreational opportunities (fishing):** Mangroves support a large diversity of fish and shellfish that use the habitats created by mangrove roots. Many species use mangrove sites as nurseries, thus nearby fishing is often very productive (Manson et al. 2005).
- **Property and infrastructure protection:** Mangroves can reduce the height and extent of coastal flooding, which in turn protects properties and infrastructure along the coast (Narayan et al. 2019).
- **Food security:** In locations where subsistence fishing makes up an important part of people's diets, productive mangrove-based fisheries can support food security (FAO 2010).

- **Tourism:** In locations where tourism infrastructure exists (e.g., hotels, boat rentals, and related services) mangrove sites can support the local tourism economy by drawing tourists to these areas (Spalding and Parrett 2019).
- **Cultural values (Moore et al. 2022):**
  - **Education and research:** Mangrove sites present opportunities to support research; some sites are locations that environmental education programs visit.
  - **Local culture/ traditions:** Mangrove systems can be important for people's sense of place, and they support activities (e.g., fishing, boating) important to local culture.
  - **Green space access:** Accessible mangroves provide a good setting for outdoor activities.

Ecological

- **Enhanced biodiversity:** Mangroves support a wide array of animal life including fish, shellfish, crustaceans, birds, and mammals (Macintosh and Ashton 2002).
- **Supports wildlife:** Mangroves support a large diversity of fish and shellfish. Many species use mangrove sites as nurseries due to the protection that these habitats can provide (Manson et al. 2005).

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 barriers specific to mangrove restoration are included here.

- **Expense**
- **Capacity**
- **Public opinion:** Community support for a project can influence whether it is implemented or not (Global Nature Fund 2015, Friess et al. 2022).
- **Conflict with other land uses**
- **Regulation**
- **Lack of effectiveness data**

Ecological

- **Project failure:** There are many occurrences of mangrove restorations failing—this mainly occurs when large-scale planting efforts are conducted in sites with unsuitable environmental conditions or in locations without community support (Lovelock et al. 2022; Friess et al. 2022).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Aguirre State Forest Mangrove Restoration Project	Puerto Rico	National Oceanic and Atmospheric **Administration (NOAA)** National Estuarine Research Reserve System (NERRS), The Ocean Foundation	Hydrological restoration	695	Estimated at least $1 million	Ongoing	Largest mangrove habitat restoration in Puerto Rico. Nursery established to support the project.	Loss of mangroves has exposed important infrastructure to damage from storm winds and flooding	No—project is just starting
Fruit Farm Creek Mangrove Restoration Project	Florida	NOAA NERRS, Florida Fish and Wildlife Commission, Florida Department of Environmental Protection, City of Marco Island	Hydrological restoration—culvert installation, clearing of tidal creeks	>200	~$3 million	More than 13 years from project planning to implementation	Restoring hydrological conditions to restore collapsed mangroves and relieve stress on current trees	No	No

Bolding indicates DOI affiliates.

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Coastal Habitats
8. Oyster Bed Restoration

DEFINITION

Oysters are a type of bivalve shellfish that reside in most coastal regions in the continental United States. As ecosystem engineers, thousands of oysters form large reefs as they attach to a hard substrate or to other oysters (NRC n.d.). Oysters inhabit both salt and brackish waters in coastal areas, providing valuable shelter for other marine species. While oysters spend most of their life cycle attached to a shell, they begin their lives as free-floating larvae (NOAA 2022). Oysters are a cornerstone of coastal ecosystems and fisheries, providing structural protection to the coast as well as improving water quality (NOAA 2022). Additionally, oysters are a staple of the seafood industry, with domestic oyster sales valued at $284.9 million in 2018 (AgMRC 2022). Oyster reefs are on the decline, with 85% of historic global oyster reefs lost (Seavey et al. 2011). This is primarily because of overharvesting, nutrient pollution, and sedimentation (NOAA 2022). To reverse this decline, oyster reef restoration and conservation initiatives attempt to restore oyster populations by lessening harvesting pressure, reducing nutrient loads, and enhancing reef habitats. Common restoration techniques include placing cultch material, installing artificial reef structures, oyster seeding, and oyster aquaculture (Olander et al. 2020a).

TECHNICAL APPROACH

Oyster reef restoration projects seek to improve the conditions for oyster reef foundation by providing hard substrates for the oysters to latch onto and, in some cases, by adding oysters to the reef area. However, many external factors influence the health of oyster reefs, including algae blooms, nutrient pollution, sedimentation, and oil spills (Olander et al. 2020b). Addressing these external factors through community engagement and other nature-based solutions such as riparian buffers will make oyster reef restoration more successful.

1. **Substrate enhancement**: Substrate is placed on the bottom of a waterbody to provide a surface for oysters to attach to. The shape, material, and location of the substrate can vary; a technique should be selected based on its desired outcome, such as shoreline stabilization or increased oyster harvest (Olander et al. 2020a).
   - **Structurally simple:**
     - **Subtidal, intensively harvested:** To restore oyster habitat, cultch material (substrate) is placed along the bed of the waterbody (Figure 1). Oyster shells are recognized as the ideal hard structure for oyster substrate and are often procured through recycling programs with restaurants (Uddin et al. 2021). However, because oyster shells are scarce, alternative substrates are often used alone or mixed with shells. A variety of alternatives have been used, including porcelain, dredged shells, limestone, noncalcium stone, other shells

besides oyster shells, and concrete. Each substrate has varying ecological, chemical, and structural outcomes that should be weighed before beginning a project (Goelz et al. 2020). Once the cultch material has been collected, it is then placed along the bed of the subtidal zone.

- **Structurally complex:**
  - **Subtidal:** While structurally simple oyster reef restoration is cheap and easy to install, the loose cultch material can be buried by sediment or degraded by wave action (Olander et al. 2020c). Larger structures with a vertical component can serve as a starting point for oyster accumulation. Artificial reef structures can be used, including oyster balls, oyster pyramids, precast concrete structures, rocks, and structures made of limestone (Figure 2; VIMS 2023). Artificial reef structures have lower larval recruitment rates than natural reefs because larvae often have trouble detecting them via chemical cues released by other oysters. Oyster colonization of artificial reefs functions as a positive feedback loop. Once oysters have attached themselves to the artificial reef, then more oysters will be attracted to the reef (Walles et al. 2016).

Figure 8.1 Depositing shell material into the water to create an oyster reef

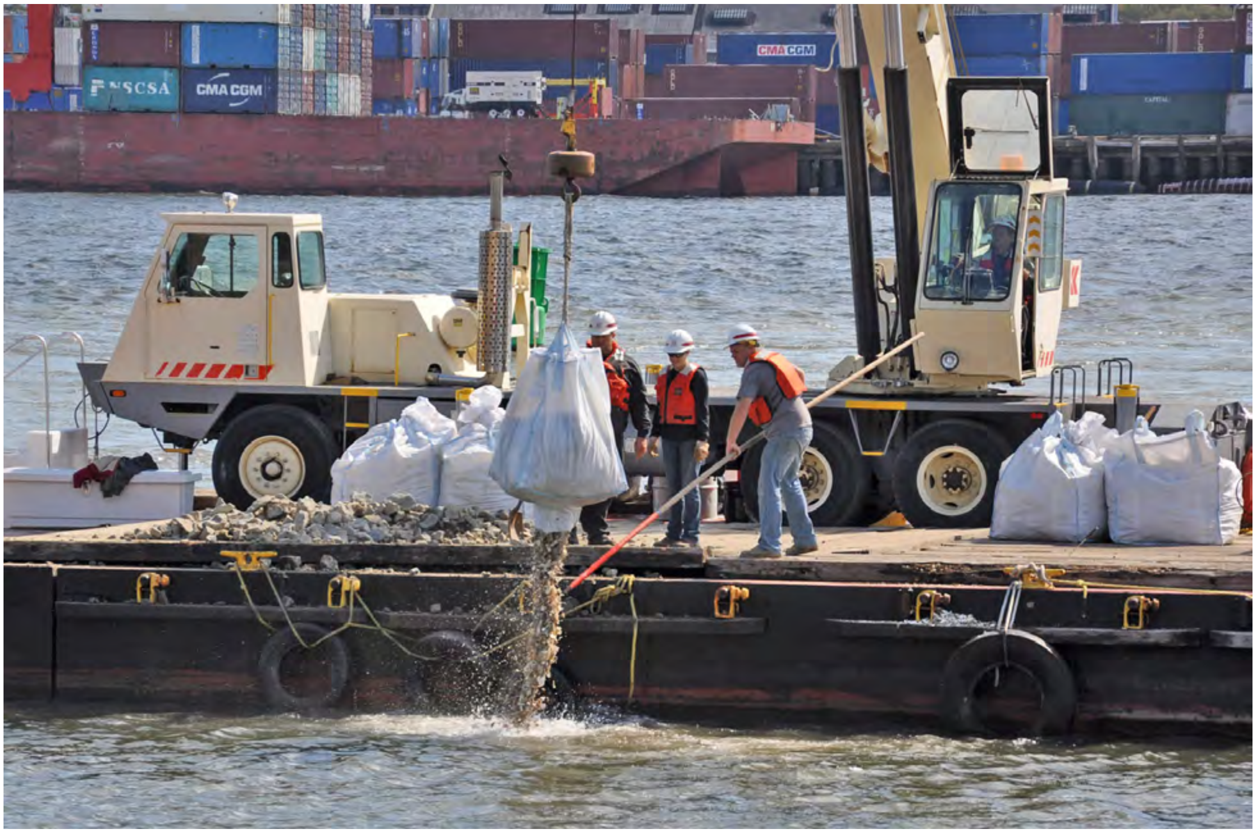

Photo courtesy US Army Corps of Engineers New York

- **Intensively harvested:** Intensively harvested artificial reefs are built primarily to reap the fisheries benefits as opposed to the water quality and shoreline protection benefits that oyster reefs provide. Intensively harvested, or *open*, reefs are generally much narrower and shorter than reefs closed to harvesting (Boulton et al. 2014).
- **Not intensively harvested:** Many restored oyster reefs are closed to intensive harvesting practices such as dredging or intensive tonging (Olander et al. 2020a). One of the advantages of not harvesting the oyster reef is that it provides a refuge for fish and crustaceans, which can then be harvested. Studies have shown that protecting an oyster reef yields a more economically valuable fish stock than if the reef was harvested for oysters instead (Grabowski and Peterson 2007).

Figure 8.2 Oyster castle artificial reef structure in the Delaware Bay

Photo courtesy US Fish and Wildlife Service

- **Intertidal:** Intertidal oyster reef restoration projects use the same structures (oyster balls, oyster pyramids, and others) as subtidal projects but are often paired with living shorelines to enhance shoreline protection. An important consideration for intertidal projects is that the artificial reef structures must be inundated at least 50% of the time to be suitable for oyster habitation. For projects that want to maximize wave and coastal flooding attenuation benefits, placing the structures in the intertidal zone is recommended (Morris et al. 2021). Intertidal reefs are not generally harvested for oysters, because oyster harvesting reduces the height of the reef, limiting the ability of the reef to attenuate waves (Wiberg et al. 2019). Thus, the benefits of oyster harvesting and wave attenuation are largely mutually exclusive and projects in the intertidal zone usually target the coastal protection benefits.
- **Oyster aquaculture**: Oysters raised in more intensively managed conditions for harvest is considered a nature-based solution because of the benefits it yields beyond its sale for consumption. Oyster aquaculture retains the water quality, coastal defense, and cultural benefits that natural oyster reefs provide (van der Schatte Olivier et al. 2020). Additionally, aquaculture reduces the demand for wild-caught oysters, allowing natural oyster reefs to regenerate. There are a variety of oyster aquaculture methods, including on-bottom, off-bottom, cage, and rack-and-bag culture. Methods vary widely based on the environmental conditions and cultural preferences of the region (Webster 2007).

2. **Oyster introduction:** Substrate placement can be followed by reef enhancement practices, such as oyster seeding or placing oysters in the reef area (Olander et al. 2020a). *Oyster seeding* refers to the process of raising juvenile oysters in a hatchery and placing them on a hard substrate to grow the reef. While seeding can provide a critical boost to reefs struggling with larval recruitment, it is expensive and has exhibited mixed results (Geraldi et al. 2013). Placing oysters in the reef area, often termed *stock enhancement*, is similar to oyster seeding except that the introduced oysters are adults instead of juveniles. Oysters are reared in “spawner sanctuaries” and then moved to the recipient reef, where they build reef structure and facilitate the natural recruitment of oyster larvae (Brumbaugh and Coen 2009).

Invasive species are a problem in oyster reefs, with invasive crabs and whelks (a group of carnivorous sea snails) causing trophic cascades that result in a decline of native oysters. Atlantic coast species are invasive on the Pacific coast, meaning that invasive species can easily integrate themselves into a similarly structured ecosystem (Kimbro et al. 2009). Oysters themselves are often vectors of invasive invertebrate species and algae, making it paramount for oyster restoration projects to be located within the natural range of the oyster species (David 2020).

OPERATIONS AND MAINTENANCE

After oyster bed restoration, ongoing invasive species removal is required. Crab traps and snail harvesting are the most effective ways to reduce populations of invasive species (NOAA 2023). In structurally simple projects, additional cultch material may need to be added if the oyster bed is not keeping up with the rate of sediment accretion and is at risk of being buried (Coen et al. 1999).

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Healthy native shellfish populations:** Healthy shellfish populations nearby indicate that the water quality and sediment concentration are good enough to host a successful oyster reef. If there are no oyster populations nearby, ribbed mussel populations can serve as a proxy for environmental health (VIMS 2023).
- ✓ **Water depth at least 1 ft at low tide**: Intertidal oyster reefs are subject to winter freezing, which will cause oysters to die off. Reefs in deeper water are less subject to being frozen (VIMS 2023).
- ✓ **Firm bottom:** A firm bottom gives a hard substrate for oysters to latch onto. It also provides a stable support for artificial reef structures to be placed on and reduces the risk of the reef being buried under sediment (VIMS 2023).
- ✓ **Accessible:** If a site cannot be reached by boat or overland routes, then it will be difficult to conduct monitoring and transport equipment needed for the restoration project. Artificial reef structures are very heavy and cannot be transported by hand (VIMS 2023).
- ✓ **Water temperature between 68–90°F:** Adult oysters can survive across a broader range of temperatures (30–120°F) but prefer more moderate temperatures. Larval oysters need consistent temperatures to survive (MCNY n.d.).
- ✗ **Salinity below 5 ppt:** Oysters thrive in areas with moderate salinity but cannot tolerate areas with low salinity or freshwater (VIMS 2023).
- ✗ **Soft mud:** Soft mud promotes the shifting and destabilization of artificial reef structures, disrupting the recruitment of oyster larvae. Furthermore, oyster reefs are more likely to be covered in sediment in areas with soft mud (VIMS 2023).
- ✗ **Disease:** As sessile organisms, oysters are especially prone to contracting pathogens. If nearby reefs have suffered from disease, then the restoration project should be sited elsewhere (Theuerkauf and Lipcius 2016).
- ✗ **Water deeper than 26 ft:** Deeper water is usually more acidic, and oysters cannot survive in highly acidic conditions (MCNY n.d.). This is increasingly becoming a prominent issue as climate change fuels ocean acidification (Ben-Achour 2022).
- ✗ **Poor water flow:** Oysters need good water flow to bring them the nutrients they need to survive. Areas adjacent to dredged channels often have good water flow, while wetlands do not (Boulton et al. 2014).

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?
A Step-By-Step Guide for Grassroots to Reef Rehabilitation	Guidebook	2008	The Reef Ball Foundation	Global	Covering both coral and oyster reefs, this guide details the use of artificial reef substrates in restoration. The authors cover permitting, site suitability, developing a timeline, and assessing site damage.	✓	✓	✓	—
Oyster Restoration	Website	2018	National Oceanic and Atmospheric Administration (NOAA)	National	NOAA provides a plethora of information relating to oyster restoration, including case studies, ideal substrates, and the use of remote sensing. Also provided is information about sustainable aquaculture and oyster gardening.	✓	—	✓	✓
Oyster Habitat Restoration Monitoring and Assessment Handbook	Guidebook	2014	NOAA, The Nature Conservancy (TNC), Florida Atlantic University, University of Southern Alabama	National	Focusing on monitoring considerations, this guide helps projects match their restoration goals with the appropriate monitoring metrics. In addition to providing common monitoring variables, the authors also discuss site selection and global oyster decline.	—	✓	✓	—
Oyster Model Inventory: Identifying Critical Data and Monitoring Approaches to Support Restoration of Oyster Reefs in Coastal US Gulf of Mexico Waters	Guidebook	2021	US Geological Survey	Gulf of Mexico but most of the information is more broadly applicable	There are many models that help determine if the environmental conditions are appropriate for oyster reef restoration. This guide helps managers parse through these models while also examining environmental drivers that influence oyster health.	—	✓	—	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Strategic Framework for Oyster Restoration Activities	Guidebook	2017	*Deepwater Horizon* Oil Spill Natural Resource Damage Assessment Trustees	Gulf of Mexico	This guide covers all stages of oyster restoration projects, leading managers through the process from planning to monitoring. The authors also cover the ecological connectivity of oyster reefs, threats to oyster populations and funding sources.	✓	✓	✓	✓
GEMS Phase I Report: Oyster Reef Restoration	Report	2020	Nicholas Institute for Energy, Environment & Sustainability; The Harte Research Institute; TNC	Gulf of Mexico	This guide helps link specific management actions to desired ecosystem services, as management choices have a large impact on which benefits a project will yield. Additional topics covered include oyster reef restoration techniques, socioeconomic outcomes of restoration and multiple case studies.	✓	—	—	✓
Restoration by Design: Great Bay Estuary, New Hampshire	Guidebook	2021	TNC	Atlantic Coast	Following the course of one specific project, the authors illustrate techniques that can be used for oyster restoration. The book delves into bathymetric surveys, community engagement, and larval recruitment.	✓	✓	✓	✓
Oyster Reef Resiliency Design Guide	Guidebook	N/A	Texas General Land Office	Gulf Coast but most of the information is more broadly applicable	This guide gives a helpful overview of the major components of oyster restoration. Filled with easy-to-read diagrams and charts, the authors help bridge the gap between engineering designs and overall project goals.	✓	—	✓	—

GRAY INFRASTRUCTURE ALTERNATIVES

Oyster bed 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 an oyster bed 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 oyster bed restoration. See the gray infrastructure alternative tables in Section 1 for a comparison of oyster bed restoration to these alternatives.

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Reduced flooding:** Oyster reefs are dynamic, three-dimensional coastal defense structures that are highly effective at attenuating waves and preventing coastal flooding. Oyster reefs reduce the amount of wave energy that impacts the shore, preventing water from traveling further inland. Oyster reefs can work in tandem with gray infrastructure such as dikes, lowering wave height so that it will not overtop the dike (Borsje et al. 2011).
- **Sea level rise adaptation and resilience:** Oyster reef restoration promotes reef accretion, allowing the reef to grow vertically as sea level rises. As reefs recruit more oysters, the amount of skeletal shell material and biodeposits increase as well. Pores in the reef structure capture sediment, facilitating sediment accretion along the coast (Rodriguez et al. 2014).
- **Storm protection:** Oyster reefs are resilient to severe storms as their strong structure can withstand powerful waves. Reefs mitigate land loss as a result of severe storms because of their ability to hold sediment in place. Oyster reefs built on hard substrates such as reef balls are better able to withstand storms, as the concrete can serve as a storm surge barrier (Walles et al. 2016).

Social and Economic

- **Resilient fisheries:** While protected oyster reefs do not allow large shellfish harvests, they can still support recreational oyster harvesting such as low-intensity tonging or hand collection (Olander et al. 2020a). Closed reefs help restore finfish stocks, as oyster reefs provide finfish with increased shelter from predators and food sources (Gilby et al. 2018). Restored oyster reefs that are open to intensive harvesting fuel oyster fisheries, which can be an economic engine for communities if harvesting occurs at sustainable levels (Breitburg et al. 2000).
- **Reduced erosion:** While degraded and overharvested oyster reefs can erode, oyster reef restoration facilitates accretion. The structurally complex nature of oyster reefs traps sediments, capturing the substrate needed to maintain land. Oyster reefs also

serve as a physical barrier shielding the coast from the direct impact of waves, reducing tidal erosion. This is especially true for intertidal restoration projects as the erosion reduction benefits become greater the closer the oyster reef is to the shore (La Peyre et al. 2015).

- **Mental health and well-being:** Oyster reef restoration improves the quality of green space, boosting mental health and psychological well-being.
- **Property and infrastructure protection:** Many coastal roadways and other vital infrastructure experience rapid rates of erosion. Oyster reefs help defend these utilities by reducing erosion rates, lessening the impact and associated rebuild costs after storms (Olander et al. 2020a). This is especially important given that many coastal communities are served by only a singular access point.
- **Jobs:** Workers will need to be hired to perform the restoration activities, boosting the local economy.
- **Cultural values:** Oysters have a profound influence on culture, with fashion, art, and architecture all inspired by oyster reefs. Indigenous communities use oysters in art and to make tools, connecting people to the environment (Thomas et al. 2022).
- **Food security:** Many communities rely on subsidence fishing for local oysters and finfish as a major source of protein. Additionally, oyster aquaculture is a source of sustainable protein that is resilient to climate change (Azra et al. 2022).

Ecological

- **Improved water quality:** Oyster reefs are highly effective at filtering water, with an adult oyster filtering as much as 50 gal of water each day (CBF 2007). Oysters get nutrition by extracting food from the water. During this process, oysters capture excess pollutants, nutrients, and sediments, significantly improving water quality. Water quality benefits are dependent on the salinity, sedimentation rates, and dissolved oxygen levels around the reef, with a healthy reef able to filter more water (La Peyre et al. 2014).
    - **Decreased nitrogen concentrations:** Oyster reefs help facilitate denitrification, reducing nutrient pollution in the surrounding water. Oysters serve as a carbon source for the denitrifying bacteria, mediating the denitrification process. As nitrogen concentrations increase, so does the rate of denitrification, suggesting that it is difficult to saturate oyster reefs as a nitrogen sink (Smyth et al. 2015).
    - **Lower water turbidity:** When filtering water, oyster reefs absorb suspended sediments, lowering turbidity. Additionally, the complex structure of oyster reefs traps sediments, taking them out of the water stream (Sharma et al. 2016).
- **Enhanced biodiversity:** Oyster restoration projects have been successful in bringing back biodiversity, providing habitat and food for finfish, birds, and invertebrates. However, restored oyster reefs do not often have equivalent levels of biodiversity as undistributed reefs, highlighting the importance of oyster conservation (Hemraj et al. 2022).

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 barriers specific to oyster reef restoration are included here.

- **Expense**
- **Capacity**
- **Public opinion**
- **Conflict with other land uses**
- **Regulation**
- **Lack of effectiveness data**

Economic

- **Overharvesting:** Many oyster reef restoration projects are undertaken primarily to replenish oyster stocks, providing economic opportunities to local communities. However, if oysters are harvested at rates faster than they can reproduce, then the oyster reef will start to erode. Intensive tonging and dredging destroy the height and width of oyster reefs. This drives further oyster decline as oysters grow faster and bigger when they are higher on reef structures (NOAA 2022).
- **Channel dredging:** Dredging to widen and deepen shipping lanes has a negative impact on nearby oyster reefs. While oyster reefs can absorb sediment, large quantities of sediment suspended by dredging can cause a reduction in filtering efficiency, reef burial via sediment deposition, and disturbance of hard substrates that oysters need (Wilber and Clarke 2010).
- **Temporary fisheries closure:** Even if overharvesting is not an issue, oyster harvesting is generally prohibited for up to two years after the restoration work has ended. This allows the reef time to enhance larval recruitment and get established (TPWD 2022). While this may harm some subsistence fishers, it is necessary to promote a successful restoration project.

Community

- **Human health impacts:** Disease is a major threat to the oyster aquaculture industry, with pathogens completely destroying oyster reefs. Furthermore, oyster diseases are difficult to predict and controlling them is difficult given the ability of pathogens to be transmitted over long distances in marine environments. Many factors play a role in oyster disease, including temperature, salinity, pH, the presence of disease vectors like phytoplankton, and the oyster microbiome. Hotter water temperatures help transmit pathogens, a critical concern given the impacts of climate change (King et al. 2019). Eating raw oysters that carry *Vibrio* bacteria can cause severe illness, with some vibriosis infections being fatal. This can be avoided by thoroughly cooking oysters before consuming them (CDC 2021).

- **Pollution:** Oysters are especially prone to aquatic pollution because of their nature as filter feeders. Nutrient pollution, toxins, and microplastics in the water are often ingested by oysters, increasing oyster mortality, and resulting in bioaccumulation further up the food chain (Scircle et al. 2020).
- **Coastal development:** Increases in coastal development drive land reclamation and dredging projects, which disturb oyster reef habitat. Additionally, urban land cover alters the sedimentation processes that allow coral reefs to accrete (Beck et al. 2009). Effluent from wastewater treatment plants also harms oysters, resulting in closures for oyster harvesting (EPA 2021).

Ecological

- **Ocean acidification:** Ocean acidification, which is caused by increased carbon dioxide emissions, reduces the availability of calcium carbonate in the water. This is an impediment to oyster reef creation as oysters need calcium carbonate to build their shells. Ocean acidification results in decreased calcification rates and oyster size and increased oyster mortality and developmental issues (Lemasson et al. 2017).
- **Surges of low salinity:** Major precipitation events, such as hurricanes, result in coastal flooding and a subsequent release of freshwater into brackish and salty coastal waters. Oysters cannot tolerate extremely low salinity conditions, resulting in mass oyster die-offs after storms (Du et al. 2021).
- **Harmful algae blooms:** Macroalgae thrive off elevated concentrations of nitrogen and phosphorus caused by nutrient pollution. This results in hypoxic concentrations and eutrophication, which causes an increase in sedimentation, burying oyster reefs (Ansell et al. 1998). Algae blooms produce toxins that accumulate in oysters, which result in mass die-offs (Jepsen 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
New York Billion Oyster Project	New York City Harbor, NY	Billion Oyster Project, New York Harbor School	Oyster cages, placing cultch material, oyster shell recycling, building structurally complex reefs	16	~65 million	9 years (ongoing)	Throughout New York's five boroughs, the Billion Oyster Project is working on 15 oyster restoration projects. Most of the projects use structurally simple substrate enhancement via placement of recycled oyster shells. Other projects have used structurally complex reefs as a part of living breakwaters.	Sea level rise, coastal flooding, severe storms	To minimize labor costs and enhance environmental education, the project has partnered with New York City Public Schools to have students volunteer at restoration sites.
Louisiana Oyster Cultch Project	Louisiana Coast	NOAA, Louisiana Natural Resources Trustees, Louisiana Department of Wildlife and Fisheries	Placing cultch material	1,421	N/A	2 years	As a part of the restoration efforts in the wake of the Deepwater Horizon oil spill, contractors placed cultch material (limestone and concrete) in six different sites across Louisiana.	No	Monitoring showed a substantial increase in oyster recruitment. However, these gains were centered around a few locations despite the same technique being used across the state.

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Little Choptank River Oyster Restoration Project	Little Choptank River, MD	NOAA, US Army Corps of Engineers (USACE), Maryland Department of Natural Resources, University of Maryland, Chesapeake Bay Program	Oyster seeding, placing cultch material	358	28.6 million	5 years	Workers reared more than 1.78 billion seed juvenile oysters in setting tanks before releasing them into the river. Stone was used as a cultch material to help enhance the substrate.	Sea level rise, coastal flooding, severe storms	The COVID-19 pandemic required managers to be flexible as they tried to keep the project on schedule.
Half Moon Reef Oyster Restoration Project	Matagorda Bay, TX	TNC, Texas General Land Office, **US Fish and Wildlife Service,** USACE, Texas A&M University	Constructing a structurally complex reef	54	5 million	2 years	Contractors installed 32 rows of oyster-encrusted rocks that rose 3 ft from the water's bed, providing structural complexity.	Coastal flooding, severe storms	The project was a success, with oyster size increasing 551% in the three years after the project was completed.
Olympia Oyster Restoration Project	Olympia, WA	Swinomish Indian Tribal Community, US Navy, Washington Department of Fish and Wildlife	Placing cultch material, oyster seeding	N/A	1 million	9 years	Volunteers placed cultch and oyster larvae across a tidal channel in the Swinomish Reservation. In areas with high predation, oysters were placed in mesh bags for protection.	No	To avoid exposing oyster larvae to the air, damp rags were placed over the cultch containing the larvae as it was transferred from the nursey to the restoration site.

Bolding indicates DOI affiliates.

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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.

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Forest Habitats
10. Forest Conservation and Restoration

DEFINITION

Forests are essential ecosystems that provide critical services to people and nature (WWF 2020). Temperate forests are the primary forest type within the United States, with boreal and tropical forests covering less area (National Geographic Society 2022). In the United States, forests cover 765 million acres, and woodlands cover 58 million acres (Perry et al. 2022). Forests provide food, fuel, oxygen, clean water, erosion control, and health benefits to people. Forests also enhance biodiversity, provide habitat, facilitate carbon sequestration, and can deliver protection from flooding and other impacts from climate change. For these reasons and others, forest conservation and restoration are crucial (WWF 2020). *Forest restoration* is the process of returning a forest to its healthy state; this can include a variety of actions such as prescribed burns, reforestation, controlling invasive species, and pruning competing underbrush (American Forests 2023). *Forest conservation* as a management practice is the maintenance of forested areas for both people and the environment. Both conservation and restoration are essential to forest management (Pawar and Rothkar, 2015).

TECHNICAL APPROACH

Forest conservation and restoration approaches vary based on the goals of the particular manager or management agency. Goals typically include both ecosystem and socioeconomic outcomes (Stanturf et al. 2017). When considering forest conservation and restoration, it is crucial to evaluate the trade-offs of timber production and ecosystem values (University of Cambridge 2022). Some primary forest conservation and restoration methods are as follows:

- **Fuels management:** Fuels management is a priority for many forests as a method to mitigate the harmful effects of wildfires, invasive species, and other disturbances. Within forests, fuels management often consists of prescribed burning and mechanical thinning (USFS 2021).
- **Reforestation:** Reforestation is one of the main practices for forest restoration. There are three main reforestation methods: natural regeneration, assisted natural regeneration, and planting (USFS 2022).
    - **Natural regeneration:** Natural regeneration allows regrowth to occur naturally. Depending on the project, natural regeneration can provide the most cost-effective reforestation method. It is essential to be aware of the species that will likely grow in these areas to ensure they will meet project goals (Chazdon 2017).
    - **Assisted natural regeneration (ANR):** ANR is a method requiring less labor and funding than planting, but aims to accelerate a forest's natural regeneration process. ANR can be achieved by improving soil, removing competing species, and mitigating disturbances (Ciccarese et al. 2012).

    - **Planting:** Some forest restoration projects require systematic planting of native species, with the best results coming from species-diverse planting projects (Ciccarese et al. 2012).

- **Controlling invasive species:** Another crucial management approach to forest restoration is invasive species management, including prevention, early detection and rapid response, long-term control, and monitoring. In long-term, large-scale forest conservation and restoration projects, prioritization is critical to ensure cost-effective management. Native tree species resistant to invasive pests can be planted to aid in stand reestablishment (NPS 2022).

OPERATIONS AND MAINTENANCE

Forest management activities often need to be repeated over time to maintain their effectiveness. The restoration activities listed previously, such as fuels management and invasive species control, will likely need to be repeated at regular intervals. Maintenance intervals will differ based on the type of forest and extent of the issue being managed.

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Disturbed sites:** Disturbance events, like wildfires or invasive species outbreaks, often create a need for forest restoration projects, specifically reforestation projects (National Forest Foundation 2023).
- ✓ **Areas conducive to natural regeneration:** Forest restoration projects in the regions that can regenerate naturally can be more cost-effective (Stanturf et al. 2017).
- ✓ **Erosion-prone soils:** Forest restoration can protect these soils and increase soil infiltration (Stanturf et al. 2017).
- ✓ **Riparian areas:** Restoring and conserving forests in riparian areas can help reduce erosion and filter sediment entering waterways. Riparian areas are often corridors for wildlife species (Stanturf et al. 2017).
- ✓ **Areas prone to disturbance:** Restoring and conserving forests prone to disturbance can lessen the severity of these disturbances, such as floods, wildfires, and invasive species invasions (Silva et al. 2023).
- ✓ **Habitat of key species:** Forests are critical biodiversity hubs, and forest conservation and restoration are often centered around specific species of concern (Ciccarese et al. 2012). One of the most prominent examples is the forest conservation and restoration movement supporting the spotted owl (USFS 2021).
- ✗ **Severely degraded sites:** While restoring severely degraded sites is important, it is often not the most cost-effective, so it is essential to consider the level of degradation when reviewing funding sources and the total budget (Silva et al. 2023).

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?
Implementing Forest Landscape Restoration: A Practitioner's Guide	Guidebook	2017	International Union of Forest Research Organizations	Global	This guide provides information for forest practitioners on implementing large-scale forest landscape restoration projects.	✓	✓	✓	✓
Increasing the Pace of Restoration and Job Creation on Our National Forests	Report	2012	US Department of Agriculture Forest Service (USFS)	National	This document details methods the USFS implements to further forest restoration efforts.	✓	✓	—	—
National Forest System Reforestation Strategy: Growing and Nurturing Resilient Forests	Strategy document	2022	USFS	National	This document outlines the national forest strategy for reforestation across the country. Reforestation is one of the most essential approaches for forest restoration, and this guide provides a framework for government agencies managing reforestation projects.	✓	✓	✓	—
Forest Service Open Space Conservation Strategy	Strategy document	2007	USFS	National	This strategy document outlines methods that government agencies can employ to promote open space conservation, including forests.	✓	✓	—	—
Sustaining Oak Forests in Eastern North America: Regeneration and Recruitment, the Pillars of Sustainability	Journal article	2014	USFS	Eastern/ Midwestern United States	This article outlines the importance of oak conservation and restoration. Oak species are some of the key targets of conservation and restoration initiatives throughout the eastern United States.	✓	✓	—	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
How Traditional Tribal Perspectives Influence Ecosystem Restoration	Journal article	2022	North Fork Mono Tribe, White Mountain Apache Tribe, USFS	National	This article emphasizes the importance of Indigenous collaboration when approaching conservation and restoration projects.	✓	—	—	✓
Forest Vegetation Simulator (FVS)	Software	Originally released in 1973; latest update in 2023	USFS	National	FVS is a tool commonly used in forestry by land managers. FVS can provide useful insight into how to conduct different forest management projects.	✓	✓	✓	✓

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Carbon storage and sequestration:** Forests sequester the most carbon of any land use type. As a result of land conversion, forest carbon stocks have been lost over the past centuries, but forest conservation and restoration can protect the carbon stocks and restore some of those that have been lost (Perry et al. 2022).
- **Reduced flooding:** Forests can play a role in flood risk reduction through various processes, including soil infiltration, evaporation, canopy interception, and creating drag on runoff, which delays flood flows (Asseily 2023).
- **Reduced wildfire risk:** Forest restoration can reduce severe fires and mitigate the risk associated with wildfires through fuel treatments and returning to historic forest conditions (Jones et al. 2021).
- **Heat mitigation:** Forests can reduce heat by releasing water vapor into the air and providing shade (Pawar and Rothkar 2015).
- **Improved air quality:** Forest conservation and restoration can lead to improved air quality as a result of the reduction of severe wildfires and by trees absorbing pollution (Perry et al. 2022).

Social and Economic

- **Jobs:** Globally, more than 1.6 billion people's income depends on forests (Aerts and Honnay, 2011). Forests within the United States are crucial for creating jobs in rural communities (USFS 2012).
- **Mental health and well-being:** Studies show that forests can have therapeutic benefits for people, including reduced stress and positive benefits for mental health disorders (Stier-Jarmer et al. 2021).
- **Cultural values:** People all over the world have a deep connection with forests. Because of extensive intergenerational and traditional knowledge of the land, Indigenous ecological knowledge about forest conservation and restoration is crucial to managing forests (Bullock 2023).
- **Recreational opportunities:** Forests across the country provide ample recreational value. Forest conservation and restoration can create and preserve these lands for human use. The USFS has estimated that the recreational value of the national forests is $14 billion annually (Avitt 2021).
- **Reduced erosion:** Forest conservation and restoration can protect erosion-prone soils by increasing water infiltration and filtering sediments (Stanturf et al. 2017).
- **Crop and timber yields:** Trees can be a renewable resource when forests are managed sustainably. Timber products are used across the world, and forest conservation and restoration can ensure longevity for timber managers. Forests can also be used for agroforestry, which integrates forest management with crop and livestock production systems (Perry et al. 2022).

Ecological

- **Enhanced biodiversity:** Forests contain more than 80% of the world's terrestrial biodiversity. It is crucial to restore forests with multiple species native to the region to achieve the best biodiversity benefits (Aerts and Honnay 2011; Ciccarese et al. 2012).
- **Supports wildlife:** Forests provide habitat for birds, mammals, reptiles, amphibians, and fish. Conversion of forest to other land types is typically the most detrimental disturbance for most species living within forests. Forest conservation and restoration provide and protect habitats for these species (Perry et al. 2022).
- **Improved water quality:** Forests are critical for watershed protection. They improve water quality because of their little soil disturbance, resulting in minimal erosion. More than half of the contiguous United States' water supply originates on forested land, occupying only 29% of the total land area (Perry et al. 2022).
- **Invasive and nuisance species management:** One of the primary operations involved with forest conservation and restoration includes invasive species management. One of the main restoration activities for invasive and nuisance species management is planting tolerant trees after removing competing species (NPS 2022).
- **Supports native plants:** Forest conservation and restoration is typically done to restore and protect native plant species (Ciccarese et al. 2012).

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 forest conservation and restoration are included here.

- **Expense:** Lack of funding is the primary obstacle forest restoration practitioners report (Cook-Patton et al. 2020). Forest restoration costs on a landscape-scale level can be in the billions of dollars. While the economic investment is high, forest conservation and restoration should be considered socioeconomic and environmental investments for the future (Wu et al. 2011).
- **Capacity:** Certain methods of forest restoration have high labor requirements, which can be a constraint in implementing these projects (Ciccarese et al. 2012).
- **Public opinion:** Public support is crucial for forest conservation and restoration on public lands. It is important to educate about the importance of the conservation and restoration work (USFS 2012).
- **Conflict with other land uses:** Forest land conversion is one of the primary causes of forest loss. This land is typically converted into development or agriculture. With the growing population, deforestation is estimated to exceed 50 million ac by 2050. Forest land conversion has lasting socioeconomic and ecological effects, and it is important to find integrated ways to sustain the growing population while still prioritizing forest conservation and restoration (Alig et al.)
- **Regulation:** Forest restoration projects can be delayed by regulatory requirements such as fulfilling National Environmental Policy Act (NEPA) and endangered species consultation requirements. However, in some cases, categorical exclusions can exempt a particular project from NEPA requirements (Fretwell and Wood 2021).

Community

- **Legal and administrative constraints:** Forest restoration is not currently occurring at the desired rate, often because of funding, legal, and organizational constraints and barriers (Jones et al. 2021).

Ecological

- **Species-poor plantations:** Forest conservation and restoration may create single-species tree plantations, which do not provide the same ecological benefits as species-diverse forests (Aerts and Honnay 2011).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Post-Fire Watershed Restoration and Monitoring in the Chiricahua Mountains of Arizona	Arizona	**US Fish and Wildlife Service,** USFS	Use of FVS to model forest management scenarios to aid in writing forest prescriptions.	Not provided	Not provided	Ongoing (began 2014)	This project aims to enhance land managers' ability to use conceptual tools and models for forest planning and identify actionable steps to increase climate resilience.	Severe wildfires, reduce invasive and nuisance species, reduce drought stress	Implementation for longer projects like this often tends to be delayed compared to short-term projects. They also learned that getting out into the field is crucial when planning these types of projects.
Blackfoot-Clark Fork Restoration Project	Montana	**Bureau of Land Management (BLM)**	Tribal collaboration and partnership, repairing damaged riparian areas	2.64 million (164,000 of BLM land)	$1.89 million from the Bipartisan Infrastructure Law (BIL) and $9.54 million from the Inflation Reduction Act (IRA)	Ongoing (began 2023)	This project aims to use BIL and IRA funding to create climate resilience, enhance recreation, restore riparian zones and wetlands, and conduct fuel treatment.	Access to clean water, reduce severe wildfires, increase carbon sequestration	Not provided

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Apache-Sitgreaves National Forest and White Mountain Apache Tribe	Arizona	USFS, White Mountain Apache Tribe	Forest restoration, rehabilitation, fuels reduction	~2 million (total forest area)	$25,427,000	1 year	This multipart project aimed at restoring forests affected by wildfires and bringing socioeconomic benefits to the area. The funding for this project came from the Forest Service Recovery Act.	Severe wildfires, protect watersheds, enhance biodiversity	One of the main lessons learned from this case study was that outcomes were enhanced when intertwining forest stewardship with community development.

Bolding indicates DOI affiliates.

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Forest Habitats
11. Green Firebreaks

DEFINITION

There are two main types of firebreaks in use in the United States. *Standard firebreaks* are areas where all organic material has been removed down to the mineral soil (Bennet 2017). *Green firebreaks* are strips of fire-resistant vegetation planted strategically to slow or stop the spread of wildfires, especially near infrastructure (Curran et al. 2018; Texas A&M Forest Service n.d.). Green firebreaks are also called *fuelbreaks*, *greenstrips*, and *greenbelts* (Ascoli et al. 2018; Davison and Smith, 1997; Greenbelt Alliance 2021).

TECHNICAL APPROACH

Green firebreaks are used as a method to stop or slow the spread of wildfire or prescribed fire, particularly in human-inhabited areas. Agencies can use existing and constructed firebreaks to achieve the same goal (Weir et al. 2017). Managers can also decide on whether or not to use firebreaks without vegetation or green firebreaks that include fire-resistant native vegetation (Bennet 2017, Curran et al. 2018).

1. **Preparation:** To construct a firebreak, a land manager needs to establish where it should go, determine the type of firebreak, and prepare the site before construction (Davison and Smith 1997).
2. **Constructing:** When constructing green firebreaks, width, naturally occurring breaks, and topography must be considered. It is also important to space out vegetation to reduce the spread of a potential wildfire (Davison and Smith 1997). In terms of vegetation, it is important to use native plants that will prevent fire spread and growth. Establishing a firebreak along a contour is best to mitigate erosion (USDA 2022). Green firebreaks can be single- or multilayered, meaning one or multiple species. Studies have shown that multilayered firebreaks are more effective. Green firebreak width depends on topography, slope, wind, typical temperature, and vegetation flammability (Cui et al. 2019).

OPERATIONS AND MAINTENANCE

After the firebreak has been constructed, it is crucial to continue monitoring and maintaining it to ensure unwanted vegetation and organic material do not build up. Firebreaks should be inspected at least annually to ensure proper functioning. Maintenance includes removing dead limbs and trees, unwanted flammable vegetation, and excessive litter. It is also essential to repair any erosion control measures (NRCS 2022). Green firebreaks can be mowed or grazed to reduce fuel buildup, particularly if grasses are included in the firebreak (Davison and Smith 1997; NRCS 2011).

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Wildland-urban interface:** In human-inhabited areas, green firebreaks are useful for the protection of life and property (Davison and Smith 1997).
- ✓ **Topography/contour:** It is best to build a green firebreak along a contour to mitigate erosion and upon ridges due to wind patterns (NRCS 2022; Cui et al. 2019).
- ✓ **Soil composition:** Soil composition is an essential consideration because more fragile soil is more susceptible to erosion (DFES n.d.).
- ✓ **Typical wind direction:** Green firebreaks should be perpendicular to prevailing winds in the region during the fire season (Cui et al. 2019).
- ✓ **Adjacent to roads and railways:** Green firebreaks can be useful next to roads or railways because of the risk of wildfire ignition from littered cigarettes and sparks from trains or vehicles (Davison and Smith 1997).
- ✓ **Continuous flammable vegetation:** Green firebreaks can be helpful in areas with continuous flammable vegetation as a method to break up the continuity (Davison and Smith 1997).
- ✓ **Low-flammability native species:** It is important to use native species to promote biodiversity. Therefore, areas with low-flammability native species are necessary for effective green firebreaks (Curran et al. 2017).

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?
A Guide to Constructing and Maintaining Firebreaks	Guidebook	n.d.	Government of Western Australia Department of Fire & Emergency Services Rural Fire Division	Although this is an Australian resource, it could be useful for land managers to see what other countries are doing	This guide provides a detailed outline of how to construct and maintain firebreaks in accordance with Australian policy.	✓	✓	✓	—
Conservation Practice: Standard Firebreak	Document	2022	US Department of Agriculture (USDA) Natural Resources Conservation Service.	National	This document provides information on how to implement and maintain standard firebreaks. It also explains essential considerations to keep in mind when constructing these interventions.	✓	✓	✓	—
Texas Prescribed Burn Handbook: Firebreaks	Webpage	2021	Texas AgriLife Extension	Written for Texas but most of the information is more broadly applicable	This resource provides specifications for firebreak widths dependent on fuel type.	✓	—	✓	—
Firebreaks for Prescribed Burning	Webpage	2017	Oklahoma State University Extension	National	This resource explains the differences between constructed and existing firebreaks and how to use them for prescribed burns.	✓	✓	—	—
Green Firebreaks as a Management Tool for Wildfires: Lessons from China	Journal Article	2019	Cui et al.	National	This resource shares knowledge from China's use of green firebreaks. China is the world leader in using this mitigation strategy to reduce wildfires, so the authors of this article synthesized some of the lessons learned into helpful information for implementing green firebreaks in the United States.	✓	—	✓	✓

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Reduced wildfire risk:** Plants with low flammability have the ability to reduce or stop the spread of catastrophic wildfires when placed strategically along the landscape within green firebreaks (Cui et al. 2019).
- **Improved air quality:** Firebreaks slow or stop wildfires and thus limit the emissions of particulate matter, greenhouse gases, and ozone (NRCS 2022).

Social and Economic

- **Property and infrastructure protection:** Green firebreaks are often used as a means of defensible space surrounding homes and farmland (Greenbelt Alliance 2021, NRCS 2011).
- **Reduced or avoided costs:** Green firebreaks require less maintenance and costs when compared to human-made firebreaks such as roads (Dosch 2020, Cui et al. 2019).
- **Firefighter safety:** All forms of firebreaks provide wildland firefighters with a defensible area to effectively fight fire and prevent the destruction of life and property (NRCS 2011).

Ecological

- **Enhanced biodiversity:** Green firebreaks can promote biodiversity by conserving native vegetation within the firebreak and reducing the potential for severe wildfires that can be detrimental to native vegetation and animals. Firebreaks allow for strategically protecting areas with high biodiversity (Greenbelt Alliance 2021). To achieve the increase in and conservation of biodiversity, it is crucial to use native plants (Dosch 2020)
- **Reduced erosion:** With the proper vegetation, green firebreaks can promote erosion control when built along a contour (Texas A&M Agrilife Extension n.d., NRCS 2022).

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 green firebreaks are included here.

- **Expense:** Although long-term maintenance can be less costly, some studies have shown that vegetated firebreaks cost more per unit area than unvegetated firebreaks (Dosch 2020; Cui et al. 2019; USDA 2014).
- **Capacity**

- **Public opinion**
- **Conflict with other land uses**
- **Regulation**
- **Lack of effectiveness data**

Economic

- **Need for other management:** Green firebreaks alone are not a highly effective strategy and often not enough to address the issue of severe wildfires (Dosch 2020).
- **Maintenance requirements:** To ensure low flammability, it is important to consistently maintain green firebreaks. Comparatively to standard firebreaks, they require less maintenance (Davison and Smith, 1997; Dosch 2020; Cui et al. 2019).

Ecological

- **Threat of invasive species:** Invasive species are a threat to green firebreaks since they often increase overall flammability (Dosch 2020).
- **Potential for catastrophic fires:** Unlike common firebreaks, green firebreaks can still burn, so it is essential to have other measures of protection from wildfires (NRCS 2011).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Paradise Nature-Based Fire Resilience Project	Paradise, CA	Conservation Biology Institute, The Nature Conservancy, and Paradise Recreation & Park District	Used mapping methods to determine ignition risks based on dominant wind direction and high-risk locations to determine the sites. Some techniques used include converting from conifer to hardwood, highlighting conservation cobenefits, and reducing fuels.	34,553 acres	Not provided	Ongoing (began 2020)	This project was designed in response to the Camp Fire that devastated Paradise, California, in 2018. The project is part of the ongoing rebuilding efforts and will test the use of wildfire risk reduction buffers, also referred to as greenbelts.	Reducing catastrophic wildfires	Not provided
Missouri – Vegetated Fire Break	Missouri	USDA	Fertilizer application, seeding operation, chemical application	3,000 ft	534.52	Not provided	This project aimed at reducing the risk of wildfires and allowing for safe prescribed burns.	Reducing wildfires, enhancing wildlife habitat	Not provided
Bureau of Land Management (BLM) Firebreak Across the Great Basin	Western United States	**BLM**	Brown strips, mowed and targeted grazing fuel breaks, green strips (Bahouth, 2020)	11,000 mi	Not provided	Not provided	This project will combine different firebreak methods to protect a 223 million ac area from catastrophic wildfires.	Reducing catastrophic wildfires	Not provided

Bolding indicates DOI affiliates.

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Forest Habitats
12. Thinning

DEFINITION

Forest thinning refers to removing trees in a forest stand to allow space for other trees and plants to grow (Punches 2004). Thinning is a silvicultural treatment used for commercial forest management and wildfire mitigation. Thinning projects are often performed as a part of larger forest land and resource management plans (USFS 2018). *Mechanical thinning* is the process of removing trees in overgrown forests to reduce the risks of extreme wildfires (Westover 2021). It is also frequently referred to as *mechanical treatment*, a more general term for any mechanized forest treatment, including mechanized cutting and hand thinning. Thinning can be done with chainsaws, crosscut saws, hand tools, bulldozers, and woodchippers (Westover 2021). As a nature-based solution, the primary goal of forest thinning is to reduce fuel and fuel connectivity to reduce high-intensity crown fires (Banerjee 2020). Thinning that is not followed by prescribed fire is not always an effective tool to combat wildfire spread, so it is essential to use them together as much as possible (Kittler 2022).

TECHNICAL APPROACH

1. **Create a plan or prescription:** Thinning projects vary greatly depending on location and forest composition; a forester should be involved in the planning and implementation of a project. When considering the number of trees to remove from a certain area, it is essential to determine what the region looked like historically. For example, south-facing slopes will have less vegetation, while drainages will have more. Treatments that focus on the removal of smaller trees as opposed to larger trees are typically more effective in reducing crown fires due to the reduction of ladder fuels (Hunter et al. 2007).

2. **Select equipment:** When conducting a thinning project, land managers can use hand tools, machines, or a mix of both (CAL FIRE 2021).

    - **Hand thinning:** Commonly used tools include chainsaws, Pulaskis, and McLeods. These tools allow crews to cut and drag the thinned debris and vegetation to the roadside or into a slash pile (CAL FIRE 2021). Hand thinning can be effective for trees less than 16 in. in diameter, on steeper slopes, or in sensitive areas (USFS).

    - **Machine thinning:** When conducting mechanical thinning, agencies typically use skid steers with various attachments such as brush rakes, grapple attachments, or masticating attachments to remove trees and other fuel from the forest (CAL FIRE 2021). Mechanical thinning is typically more cost-effective and can be very useful in the removal of large trees, but it is prohibited on slopes greater than 30% and in sensitive areas (USFS). Another form of forest machine thinning is *mastication*, which is a method of using heavy machinery to grind up fuels (Northern Colorado Fireshed Collaborative 2023).

3. **Remaining slash:** After conducting either hand or machine thinning, there are multiple ways to handle the *remaining slash*, which is the residual woody debris (Murray et al. 2022). Many considerations go into deciding which method to use, including costs, capacity, and invasive species management (DeGomez 2014).
   - **Mastication:** Mastication uses machinery to break down slash and spread it across the forest floor (Northern Colorado Fireshed Collaborative 2023). Excavators with masticator attachments can create breaks in fuel to provide fire breaks and safety for firefighters (CAL FIRE 2021).
   - **Chipping:** Chipping of slash is a method often used for thinning projects to change the shape of the slash to reduce the risk of large wildfires (CAL FIRE). Chipping is appropriate to reduce catastrophic fire danger but can lead to the death of low-level plants if the chips are dried out (Glitzenstein 2009).
   - **Piles:** Slash is often collected and moved into piles by machine or hand (Figure 1). These piles are dried out for a few years and then burned (USFS).
   - **Commercial sales:** Often, agencies will perform commercial thinning, which combines wildfire mitigation work with generating funds (Figure 2). The most significant barrier to thinning projects is often the cost, which can be covered with commercial sales of woody products (Chang et al. 2022; Johnston et al. 2021).

Figure 12.1 Slash piles created after thinning for fuel reduction

Photo courtesy Oregon State University

- **Prescribed burn:** Prescribed burns are typically used after a thinning project to further reduce hazardous fuels (CAL FIRE 2021).

4. **Monitoring:** Monitoring is a crucial final step of a thinning project to determine if the project was effective and should be repeated in similar forest types or the same site in the next 20 or 30 years, depending on the forest's needs. Monitoring also builds public confidence in fuel treatment projects (Hunter et al. 2007).

OPERATIONS AND MAINTENANCE

Thinning (and associated prescribed burning) will need to be repeated over time to maintain effectiveness. The number of years between thinning treatments will differ based on the type and age of a forest.

Figure 12.2 Commercial thinning project in Washington

Photo courtesy US Forest Service—Pacific Northwest Region

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Coniferous tree species:** Thinning treatments more effectively reduce catastrophic wildfires in coniferous forests than in broadleaf forests (Moreau et al. 2022).
- ✓ **Wildfire threat:** The areas defined by the US Department of Agriculture (USDA) and Department of the Interior (DOI) as the highest priority for fuel treatments are the entire Mountain West, West Coast, Southwest, and Southeast (USDA and DOI n.d.).
- ✓ **Community buy-in:** Because of the potential controversy of thinning projects, it is essential to have community buy-in and engagement to create collaborations and partnerships (Thompson 2021).
- ✓ **Weather and climate:** Decomposition rates are essential when considering whether to conduct a thinning project, especially when using thinning to reduce severe wildfires (Moreau et al. 2022). Studies have shown the faster decomposition after thinning projects results in lower fire severity (Palmero-Iniesta et al. 2017). Decomposition occurs more quickly in climates with heavier rainfall.
- ✓ **Areas affected by insects or disease:** Areas affected by dwarf mistletoe and mountain pine beetle are good sites for thinning projects (Hunter et al. 2007).
- ✓ **Drought-prone:** Because thinning can reduce drought stress, particularly drought-prone areas are good sites for thinning projects (NSF 2018).
- ✗ **Limited work capacity:** Many federal agencies have limited capacity for thinning projects, so sites without agency investment may be challenging to thin (Hunter et al. 2007).
- ✗ **Steep slopes:** To conduct effective large-scale thinning projects, machinery is typically the most efficient and often cannot be used on slopes steeper than 30%. For large-scale thinning projects, steep slopes create an extra challenge (USFS, CAL FIRE 2021).

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 Thinning Ponderosa Pine for Improved Forest Health and Fire Prevention	Guidebook	2014	University of Arizona College of Agriculture & Life Sciences Cooperative Extension	Western United States (anywhere ponderosa pines are managed)	This guide provides information on how to thin a ponderosa forest. This includes stocking rate, basal area, and deciding which trees to mark.	✓	✓	—	✓
Fuels Reduction Guide	Guidebook	2021	California Department of Forestry & Fire Protection	California (national applications, but most relevant in the western United States)	This guide provides information on how to conduct a variety of fuel reduction projects.	✓	—	✓	✓
A Comprehensive Guide to Fuels Treatment Practices for Ponderosa Pine in the Black Hills, Colorado Front Range, and Southwest	Guidebook	2007	USDA Forest Service (USFS)	Western United States (anywhere Ponderosa pines are managed)	This guide provides recommendations for various fuel treatments within ponderosa pine forests. It includes social, political, economic, and ecological factors regarding fuel treatments.	✓	✓	✓	✓
Community Wildfire Mitigation Pocket Guide	Guidebook	2021	Coalitions & Collaboratives	National	This guide provides information for community managers on many different wildfire mitigation practices, including forest thinning.	✓	✓	✓	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
National Priorities for Broad-Scale Fuels Management	Map	n.d.	USDA and DOI	Continental United States	These maps show priority areas for fuel management efforts throughout the continental US.	—	✓	—	—
Forest Vegetation Simulator (FVS)	Software	1973	USFS	National	FVS is a tool commonly used in forestry by land managers. FVS can provide useful insight into how to thin for various goals, especially the Fire and Fuels Extension.	✓	✓	✓	✓
The Fire and Fuels Extension to the Forest Vegetation Simulator: Updated Model Documentation	Guidebook	2010	USFS	National	The Fire and Fuels Extension from FVS is a helpful tool for forest fuel management. This guidebook provides examples, stand visualizations, and outputs from the software.	✓	✓	✓	✓
A Land Manager's Guide for Creating Fire-Resistant Forests	Guidebook	2013	Oregon State University, Northwest Fire Science Consortium	Written for the western United States but most information is more broadly applicable	This guide provides information on different silvicultural treatments used to create and manage fire-resistant forests.	✓	✓	✓	—

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Reduced wildfire risk:** The most common climate-related goal of thinning is to reduce the risks of catastrophic wildfires. Thinning projects can reduce fires by decreasing fuel loads, alleviating tree stress, increasing space between trees, and reducing ladder fuels (Willis et al. 2022). Thinning can also increase the fire-tolerant species in a stand, which provides a more long-term benefit (Moreau et al. 2022).
- **Drought mitigation:** Many forests throughout the United States are overgrown as a result of long-running fire suppression practices. This overgrowth and increased evapotranspiration contribute to water shortages in these areas. A reduction in trees in the forest can reduce water stress in drought-sensitive regions (NSF 2018).
- **Improved air quality:** As a result of the subsequent decrease in severe wildfires, thinning projects have the potential to positively impact air quality (Westover 2021, Campbell 2022).
- **Carbon storage and sequestration:** Studies have shown that effective thinning treatments can increase carbon storage and sequestration (Collalti et al. 2018; Schaedel et al. 2016). Forest thinning can pose a carbon trade-off: while it does reduce carbon storage in the short term, in the long term it can allow for more carbon storage because of an increase in tree health and reduction in catastrophic wildfires (Folkard-Tapp et al. 2021).

Social and Economic

- **Property and infrastructure protection:** Thinning is often done within the wildland-urban interface (WUI), the area where people live within fire-adapted and fire-prone ecosystems. These thinning projects reduce the potential for catastrophic wildfires that could damage personal property and infrastructure (NPS 2017).
- **Jobs:** The USFS is increasing firefighter capacity funding by $259,180,000 moving into 2024, and these new employees will aid in thinning projects on USFS land (USFS 2023). DOI is planning to increase the firefighting workforce by 17,000 positions by the end of 2023 (DOI 2023). Many federal jobs are being added through the increase in fuel management projects.
- **Agriculture and timber yields:** Thinning is often done commercially, meaning the cut trees are sold for wood or other woody materials. This process can benefit future forest harvests and provide funding for agencies, organizations, or private landowners to perform thinning projects that offer various benefits (Hunter et al. 2007).

Ecological

- **Supports native plants:** Thinning treatments have been shown to increase tree growth (Hood et al. 2016) and lead to stronger and more resilient residual trees, which are more resistant to disturbances (Moreau et al. 2022). One of the main goals of thinning and fuel reduction projects is to bring the forest back to historical conditions (Hunter et al. 2007).

- **Invasive and nuisance species management:** Thinning can mitigate the impacts of insect damage within forests because of the reduction in stressed trees, to which pests are typically more attracted. Thinning can reduce the vulnerability of stressed trees by making it harder for insects to locate stressed trees, increasing moisture and sunlight entering through the canopy, and decreasing competition for the residual trees (Willis et al. 2022). Dwarf mistletoe and mountain pine beetle outbreaks are often treated with thinning projects (Hunter et al. 2007). Another study found that resin ducts increased after thinning projects in thinned ponderosa pine forests, which increased the trees' resistance to the mountain pine beetle (Hood et al. 2016). USFS has found that thinning projects help to reduce the establishment of flammable invasive species such as nonnative cheatgrass (Westover 2021).

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 thinning are included here.

- **Expense:** Thinning project costs have an extensive price range dependent on the method, terrain, and equipment used. The cost of thinning ranges from $758 to $4,291 per hectare (~$307 to $1,737 per acre) for forests in the western United States (Chang et al. 2023).
- **Capacity:** Most federal agencies have limited resources to conduct thinning projects at large scales because of the staffing, funding, and time needed (Hunter et al. 2007). New federal legislation, such as the Bipartisan Infrastructure Law and Inflation Reduction Act, has provided increased funding to mitigate capacity and resource issues (DOI 2023).
- **Public opinion:** There are many conflicting reports on the efficacy of thinning, specifically targeting organizations that do commercial thinning projects for wildfire mitigation and therefore profit from the thinning project. Many environmental groups are adamantly against thinning practices. Both sides of the argument scientific research backing up their claims, so thinning is still considered a controversial practice (Thompson 2021).
- **Conflict with other land uses**
- **Regulation**
- **Lack of effectiveness data**

Community

- **Aesthetics:** The residual trees, piles, and other marks of a thinning project are often not well-received by the public, especially when they are in highly frequented areas (Hunter et al. 2007).

Ecological

- **Potential for increased fire activity:** Research has shown that if thinning is done at a low level, fire activity may increase as a result of the rise in wind speed when canopy moisture is low. Thinning at a higher level was shown to reduce fire severity, but fire spread might still be increased. It is essential to know what implications thinning may have on a specific site (Banerjee 2020). Increased fire severity may also be a threat if the fuel load left from the thinning project is not properly treated (i.e., removed or burned) (Hunter et al. 2007).
- **Susceptibility to ice storms:** Thinning projects in the southern United States have resulted in forests being more susceptible to damage and bending from ice storms because the residual trees are often weaker and have fewer neighboring trees that can support each other (Willis et al. 2022).
- **Wind damage to forests:** Thinning projects can increase a forest's susceptibility to wind damage by opening up the stand, which takes away windbreaks and increases the space between trees. Trees typically become more wind resistant within 2 to 10 years after a thinning project is completed (Willis et al. 2022; Moreau et al. 2022).
- **Invasive species:** Invasive species frequently do well in disturbed environments, which thinning creates, so it is essential to be aware of the potential establishment of invasive species (Hunter et al. 2007).
- **Removal of habitat:** Some species prefer open stands, like various ungulates, while others prefer dense stands, like the spotted owl. It is also a common thinning practice to remove snags (standing dead trees) for human safety from both wildfires and fallen trees. Snags provide excellent habitats for many wildlife species. For these various reasons, it is vital to retain a variety of stand structures when implementing fuel treatment plans (Hunter et al. 2007).
- **Soil degradation:** Conducting a thinning project using heavy machinery can lead to soil compaction and displacement, which can affect the plants in the area. The buildup of slash, chips, and other woody material on the ground can also change the composition of the soil. Soil degradation can be avoided using hand crews or smaller, more maneuverable machines (Hunter et al. 2007).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Forest Fuel Treatment Efficacy in BC	British Columbia, Canada	BC Wildfire Service, Ministry of Forests, Lands, Natural Resource Operations and Rural Development	**Fuel treatments, including thinning, debris removal, and ladder fuel reduction**	2 to 22 hectares, dependent on the site	$1,800 to $3,800 per hectare	9 years (case study examining 10 fuel management treatments)	This case study looked at the different methods to reduce wildfire severity to see if previous treatments had an impact on wildfires that went through the treatment areas.	Catastrophic wildfires	Fuel treatments (thinning, debris removal, and ladder fuel reduction) were effective and feasible on large scales. Fuel treatments that left up to 25 tons/hectare were still effective as long as the fuels were patchy.
Oakridge/Westfir Thinning & Fuel Reduction Project	Oregon	USFS; Hazeldell Rural Fire District; Oakridge, OR; Westfir, OR	Mechanical commercial and non-commercial thinning, prescribed fire, creation of fuel breaks	~4,200 acres	Not provided	Ongoing (began 2007)	This long-term project is designed to continually reduce wildfire risk to communities near the project sites.	Reduce long-term fire risk, habitat restoration	Not provided
Oregon Mountain Forest Health and Thinning Fuels Reduction	Weaverville, California	**Bureau of Land Management**	Upland and riparian zone thinning with emphasis on unhealthy trees, removing horizontal and vertical fuel continuity	139 acres	Not provided	2 years (total project time including archeological site assessment)	This project was designed to conduct thinning and post-thinning activities within the WUI. Specifically, the project focused on removing unhealthy trees and conifers encroaching on oak woodlands.	Wildfire and fuel management, wildlife protection.	Not provided

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Saint Vrain Forest Health Partnership Project	Boulder, Colorado	St. Vrain Forest Health Partnership; The Watershed Center; Boulder County, CO; Longmont, CO; Boulder Valley and Longmont Conservation Districts; Colorado State Forest Service; USFS- Arapaho, Roosevelt, Pawnee Boulder District	Hand thinning, mechanical thinning	Current project area: 380 acres (total project area: ~ 4,000 acres)	$3,477,770	Ongoing (began 2023 and runs through at least 2025)	This project aims to implement fuel reduction to provide infrastructure and human protection.	Reduce catastrophic wildfires	Not provided
North Cherokee Park	Larimer County, Colorado	Larimer Conservation District	Mechanical thinning, whole-tree harvest	625 acres	$1,560,000	Not provided	Multilandowner forest restoration project.	Reduce wildfire risk, restore forest health	Not provided

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Grasslands/Sagebrush Habitats
13. Grassland Conservation and Restoration

DEFINITION

Grasslands, often called *prairies* in the United States, are habitats where the dominant vegetation type is grass. Though trees may be present, there is often not enough precipitation to support a forest ecosystem. Grassland habitats are typically maintained through a combination of limited precipitation, fire, and grazing animals (National Geographic Society n.d., Buisson et al. 2022). Intact grasslands support high levels of biodiversity and have high conservation value from the numerous benefits they provide, including pasture forage, water regulation, erosion control, support for pollinators, and carbon storage and sequestration. However, grassland habitats have been severely degraded in many areas of the world and continue to be threatened by land cover conversion to agriculture, woody encroachment, altered fire and grazing regimes, urbanization, invasive species, and climate change (Buisson et al. 2022; Török et al. 2021). In the US Great Plains region, more than half the original grasslands have been lost (Buisson et al. 2022). Grassland restoration is important given the amount of these habitats that have been lost and the immense value they provide. Despite their value, there is relatively little focus on grassland restoration research compared to that for forests, wetlands, and rivers (Buisson et al. 2022; Török et al. 2021).

TECHNICAL APPROACH

Grassland restoration may seem simple. However, reestablishing “old-growth” grasslands (akin to old-growth forests) takes a lot of time and effort, and restored grasslands do not typically deliver all the same (or the same level of) functions as pristine grasslands (Buisson et al. 2022). Grassland restoration techniques vary depending on the beginning state of the target site; however, they typically involve three main steps: site preparation, plant/ seed selection, and revegetation (Gornish and Shaw 2017).

1. **Site preparation**: Site preparation involves management to create conditions conducive to native grassland vegetation. This typically involves addressing and mitigating key negative disturbances to the site (Gornish and Shaw 2017). Preparation of the site depends on findings of an initial site assessment that examines previous use of the site, soil moisture, slope, and existing vegetation (Phillips-Mao 2017a, b). Site preparation activities may include:

    - **Invasive species/weed management:** Native plants often will not establish on a site where invasive plants dominate. Therefore, invasive plants need to be removed from a site before revegetation can occur. Invasive removal can be done through use of prescribed burns, herbicides, mowing, or managed grazing. It is not unusual for multiple invasive control techniques to be required for a single site, and repeated treatments may be necessary. Additionally, timing invasive control techniques can be important to target invasive plants at particular life stages

(Gornish and Shaw 2017). If possible, spending two growing seasons on weed/invasive control at the beginning of a project can help prevent the invasives from returning to the site (Phillips-Mao 2017a, b).

- **Addressing compaction:** Soil compaction is often an issue at sites where intensive grazing has occurred or vehicles/farm equipment have repeatedly driven over the soil. Compaction can prevent root growth and water infiltration, which makes revegetation with native plants difficult. Compaction can be reversed by subsoiling or ripping the soil using a field cultivator or a ripper (Benson et al. 2011). Tilling the soil has been linked to changes in soil carbon, so decisions to till should be made with this in mind (Young et al. 2021).
- **Managing elevated nutrients:** In some cases, grasslands may be restored on sites where excessive nutrients were applied to the soil. To reduce nutrients in eutrophic soils, a variety of techniques can be used, including topsoil removal, high-yield crop cultivation to deplete nutrients, mulching, controlled burns, grazing, mowing, and haying (Lyons et al. 2023).
- **Addressing overgrazing:** Sites that have been overgrazed may require reduced grazing access or grazing exclusion, especially during early stages of a project (Dicks et al. 2020).
- **Hydrological restoration:** In some cases, the natural hydrology of a site may have been altered during historic land use and will need to be restored. This may involve removing water diversion structures such as ditches or drainage tiles (Phillips-Mao 2017a, b).

2. **Plant selection**: Choosing plants that will thrive at the restoration site is very important. Species should be selected based on site conditions (soil type, slope, aspect, elevation, presence of grazing, climate, and so on) as well as restoration goals. Look for local guidance regarding species mixes well-suited to the region and conditions of a particular site. For example, Appendix A of the Restoration Manual for Annual Grassland Systems in California contains detailed decision support for selecting plant mixes based on existing site conditions. Many state natural resource agencies have similar guidance. Using a nearby healthy grassland reference site can also be helpful in selecting a good plant mix. Selecting a diversity of species for planting is important to help provide a diversity of functional traits that enhance plant community stability as well as contribute to a variety of ecosystem services (Gornish and Shaw 2017). Plant selection can also be influenced by particular restoration goals. To support pollinators, selecting a mix of plants that flower at different times during the growing season can provide more consistent pollinator resources. To help control erosion, species that grow rapidly and provide fast ground coverage can be selected. For grazing support, plant mixes that have low toxicity, rapid establishment, high growth rates, and high protein content are best. To support carbon storage, seed mixes with a majority of perennial grasses combined with sufficient fertilization will help enhance carbon sequestration (Gornish and Shaw 2017).
3. **Revegetation**: After plants have been selected, they need to be seeded at the site. Timing of planting is important and local guidance about planting times should be

followed. It is possible to seed an entire restoration site, but also to seed a subset of site patches and allow natural regeneration across the entire site in following seasons (also called *strip seeding* or *spatially patterned seeding*). Seeds can be applied to the site in multiple ways, including broadcast seeding by vehicle or by hand, aerial seeding by aircraft, hydroseeding (spraying a slurry mixture of seed, mulch, and fertilizer), and drill seeding (dispensing seeds from a seed hopper on a tractor). Typically, grassland revegetation is accomplished using seeds because of cost constraints, but introducing established plants can help enhance restoration in some cases by providing erosion control, shade, landscape heterogeneity, and reducing the chances of exotic/ invasive reestablishment (Gornish and Shaw 2017).

OPERATIONS AND MAINTENANCE

Weed management is a key maintenance activity at restored grassland sites because early stage native plants are susceptible to competition by invasives. Weed management can be accomplished in a variety of ways, including selective herbicide use, burning, and mowing. Managing weeds will be most important in the first few years after revegetation (Gornish and Shaw 2017; Phillips-Mao 2017a, b).

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Historic grassland sites:** Typically, grassland restoration is successful on sites that historically have been grassland and have been either degraded or converted
- ✓ **Disturbance:** Grasslands are maintained through a disturbance regime that limits woody encroachment (e.g., limited precipitation, grazing, fire, and so on). The site should have either expected natural disturbance or sufficient funds to introduce disturbance that will maintain the restored grassland
- ✗ **Nearby herbicide use:** It can be difficult to establish native grasslands in areas with herbicide drift from neighboring crop fields.

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?
Restoration Manual for Annual Grassland Systems in California	Guidebook	2017	University of California, Division of Agriculture and Natural Resources	Designed for California but most of the information is more broadly applicable	This guide helps users select grassland restoration goals and implement those goals with technical guidance on grassland restoration activities. It also contains a guide to help with native plant selection for California sites.	✓	—	—	—
Shrub-Steppe and Grassland Restoration Manual for the Columbia River Basin and accompanying Case History Library	Guidebook, document	2011	Bonneville Power Administration, Washington Department of Fish and Wildlife, Bureau of Land Management	Designed for the Columbia River Basin, WA, but most of the information is more broadly applicable	This manual contains information useful for planning, implementing, and maintaining grassland restoration projects. The case history library documents learnings from case studies from the target region.	✓	—	✓	✓
Restoring Your Degraded Grassland to Conservation Prairie	Guidebook	2017	The Nature Conservancy	Designed for Minnesota but most of the information is more broadly applicable	This guide is targeted at landowners who want to transform their degraded grasslands into conservation prairies. It gives high-level guidance and helps set expectations for what such a project might entail.	✓	—	✓	—

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Carbon storage and sequestration:** Most carbon storage in grassland systems takes place belowground—90% of carbon in these systems is stored as root biomass or soil organic carbon (Ontl and Janowiak 2017, Bai and Cotrufo 2022). Though intact grasslands typically store more carbon than restored grasslands, it has been found that management practices, including conversion of cultivated areas to grasslands, increasing plant diversity, sowing legumes and grasses, and fertilization can help enhance carbon storage and sequestration in restored grassland systems (Bai and Cotrufo 2022).

Social and Economic

- **Reduced erosion:** Grassland vegetation helps stabilize soil and reduce erosion, especially as compared to croplands (which is often an alternative land use for grassland sites) (Bengtsston et al. 2019).
- **Recreational opportunities:** Many popular recreational activities like birdwatching, hiking, and hunting take place in grassland systems (Bengtsston et al. 2019).
- **Agriculture and timber yields:** Where managed grazing is allowed on grassland systems, these habitats can provide important fodder to grazing livestock (Bengtsston et al. 2019).
- **Cultural services:** Grassland systems have been known to be associated with cultural heritage, containing certain sacred places and linkages to traditional livelihoods (Bengtsston et al. 2019).

Ecological

- **Enhanced biodiversity:** Healthy grasslands can host extremely high numbers of species, many of which are grassland specialists and endemics. High numbers of plant species can exist within a relatively small area, supporting high biodiversity and multiple ecosystem functions (Petermann and Buzhdygan 2021).
- **Supports wildlife:** Healthy grasslands host a species-rich wildlife community both below- and aboveground, with especially high numbers of insect species, including pollinators. Grasslands also host some of the last remaining populations of large mammalian herbivores as well as a wide variety of birds (Petermann and Buzhdygan 2021).
- **Enhanced soil health:** Grassland systems help maintain and improve soil health; the breakdown of grassland plants and roots after each growing season helps establish rich organic matter in the soil (Ontl and Janowiak 2017; Bai and Cotrufo 2022).

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 grassland conservation and restoration are included here.

- **Expense**
- **Capacity:** There has been relatively little research on grassland restoration, as opposed to restoration of other habitats like forests, wetlands, and rivers. Limited research restricts knowledge of how to effectively restore these habitats (Török et al. 2021).
- **Public opinion:** In some cases, it has been found there is relatively little public support for grassland restoration because grassland restoration benefits are not widely recognized (Lyons et al. 2023).
- **Conflict with other land uses**
- **Regulation**
- **Lack of effectiveness data**

Ecological

- **Establishment and disturbance:** Grassland restoration challenges include difficulty establishing native seeds successfully and difficulty establishing an appropriate disturbance regime for restored sites (Török et al. 2021).
- **Seed availability:** In some cases, a lack of availability of suitable native plant seeds has been reported as a challenge (Lyons et al. 2023).
- **Invasive species:** Removing and continuing to prevent intrusion by invasive species is a constantly cited challenge to grassland restoration (Lyons et al. 2023).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Duralde Cajun Prairie Restoration	Evangeline Parish, LA	**US Fish and Wildlife Service (USFWS)**	Mechanical clearing of invasive trees, removal of levees, reintroduction of native plants through transplantation and seeding	334	Not provided	Not provided	Restoration of coastal tallgrass prairie that had been degraded from agricultural activity and livestock use	No	It was discovered that transplanted native plants survived better than seeded ones and that seeded areas took up to 10 years to recover.
Rotational Cattle Grazing to Restore Degraded Chihuahuan Desert Grasslands and Promote Watershed Health	Marfa, TX	Dixon Water Foundation, Rio Grande Joint Venture, Bird Conservancy of the Rockies, Borderlands Research Institute, Natural Resources Conservation Service	Introducing rotational grazing that mimics natural bison movement to prevent overgrazing and conversion of grasslands to bare ground	11,000	Not provided	Not provided	This restoration effort restored grasslands that had been degraded through many years of overgrazing by cattle. Rotational grazing restored the grassland habitat and prevented runoff and accelerated flows throughout the watershed.	No	Monitoring is ongoing to help with adaptive management.
Prescribed Burns for Grassland Management at the Sevilleta National Wildlife Refuge	Sevilleta National Wildlife Refuge, La Joya, NM	US Department of Agriculture—Forest Service, **USFWS,** University of New Mexico, Sevilleta Long Term Ecological Research	Prescribed burns to increase native grass cover in existing grasslands	>20,000	Not provided	Not provided	This grassland management activity (prescribed burning) has the primary goals of contributing to new knowledge on fire, increasing native grass cover, and identifying the most effective burn treatments to promote native plant communities	No	Various burn treatments are applied to contribute to knowledge about how to apply prescribed fire for effective native plant recovery

Bolding indicates DOI affiliates.

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Grasslands/Sagebrush Habitats
14. Sagebrush Conservation and Restoration

DEFINITION

Sagebrush habitats exist across the western United States in areas with hot, dry summers and cool, moist winters. They are dominated by big sagebrush (*Artemisia tridentata*) vegetation and perennial grasses (Pyke et al. 2015). Almost half of historic sagebrush habitat has been lost to land use conversion and invasive plants. Remaining sagebrush areas are increasingly invaded by nonnative annual grasses, fragmenting patches of big sagebrush and making the ecosystem less suitable for dependent wildlife, most notably the greater sage-grouse. Fire suppression, grazing, and invasive plants in sagebrush habitats have also altered the historic fire regime, leading to increased tree cover and higher potential for severe wildfires. Sagebrush restoration aims to restore sagebrush vegetation communities to their original state by promoting growth of a mix of big sagebrush and perennial forbs and grasses while eliminating invasive plant species.

TECHNICAL APPROACH

The US Geological Survey (USGS) and Department of the Interior (DOI) Restoration Handbook for Sagebrush Steppe Ecosystems with Emphasis on Greater Sage-Grouse Habitat describes two main approaches for sagebrush restoration, summarized as follows (Pyke et al. 2015, 2017):

- **Passive restoration:** Passive restoration facilitates the growth of desirable plant species by changing management to facilitate natural processes that shift plant species composition. This is likely to be successful in less-degraded habitats where native perennial grasses still exist; if annual grasses already dominate, active restoration is likely needed. Passive restoration usually changes the grazing regime by adjusting the level and season of use for grazing, depending on the initial vegetation community and desired outcomes. This may require the use of herding, fencing, or adjusting water availability to spread grazing pressure across a larger area or rotate animals between different parts of the habitat.
    - **Grazing—start of growing season:** Grazing in the early growing season and resting pastures (eliminating grazing) during the fastest growth and reproductive season of perennial grasses and forbs supports their growth and population and can increase their competitiveness against invasive species, including cheatgrass. Specific growing seasons vary by geography and climate.
    - **Grazing—after flowering:** Grazing cattle in sagebrush after herbaceous plants have flowered tends to benefit the sagebrush vegetation because cattle preferentially graze herbaceous plants and avoid sagebrush. This can be helpful for promoting sagebrush growth, but repeated grazing can result in overly dense sagebrush that prevents herbaceous plant growth.

    - **Grazing—end of growing season:** Resting pastures at the end of the growing season allows vegetation to reach its full height to provide cover and nesting habitat for wildlife, including the greater sage-grouse. It may take several years for the full effects of this strategy to occur.
    - **Grazing—dormant season:** Grazing during the dormant season minimizes adverse impacts on perennial grasses and forbs and may benefit herbaceous plants by focusing grazing pressure on sagebrush, but also removes cover used by the greater sage-grouse during its nesting season. It is important to consider potential adverse habitat impacts and proceed with caution if using this approach.

    Passive restoration may also restrict recreational access to restoration areas to avoid transporting invasive seeds into the area. Alternatively, vehicle cleaning can be required before access to the restoration area to remove invasive seeds.

- **Active restoration:** Active restoration directly modifies the plant community by removing undesirable species or adding desired species. This active approach is required when desired native plant species have been degraded to the point that they are not likely to recover under passive restoration or when invasive or other undesirable species already dominate the site. The general process for active restoration is as follows:

    1. **Controlling undesirable plant species**: Active restoration is frequently done in areas dominated by invasive or other undesirable species that must be controlled before desired species can be planted. There are multiple approaches to control undesirable plant species:

        - **Prescribed fire:** Prescribed fire can be used to remove fire-sensitive species and to temporarily reduce woody plant cover, which is helpful for equipment access for other plant control techniques or seeding. See the prescribed fire strategy summary for more information about this strategy. Fire in sage-grouse areas can reduce habitat suitability for decades (an exception is sage-grouse habitats at high elevations with mountain big sagebrush, which is more resilient to fire and can recover more quickly), so caution is advised when considering the use of prescribed fire in sage-grouse habitat. In areas without sage-grouse, fire can reduce woody plant dominance and reduce annual grass populations for a few years. This depends on fire intensity and duration sufficient to kill seeds in the soil, which can be difficult to achieve under safe burning conditions.
        - **Mechanical treatments:** These range from harvesting individual trees (often done by hand in areas where sagebrush exists) to mowing or pulling pipes or chains between tractors to remove plants and disturb the soil. Many of these techniques have high potential for soil disturbance (which facilitates erosion) and damage to desirable plants as well as target plants, so positive and negative impacts should be considered when selecting a mechanical treatment.

- **Chemical treatment (herbicides):** Herbicides can also be used to control undesirable plants. Many herbicides used for annual grasses are nonselective (kill all plants), but the rate and timing of applications can be used to target certain types of plants. There are some selective herbicides for woody plants and shrubs that can be used to reduce sagebrush growth. Use caution when selecting and applying herbicides, considering the potential for adverse effects on desired plant species and subsequent impacts on sage-grouse habitat.
- **Biological control:** This includes the use of insects, microbes, or livestock to target undesirable plants. Insects or microbes usually require permitting because they are often imported from the same country the invasive plant originated from. Certain woody plants can be controlled with insects (e.g., saltcedar, leafy spurge); no microbial pathogens are currently approved for use to control invasive grasses, but research is ongoing. Targeted grazing using livestock does not require permits, but trained livestock may be required to ensure only target species are grazed.

2. **Soil rehabilitation:** This step may be needed to remedy unconsolidated surface soils or compacted subsurface soils. Firm surface soils are needed to optimize germination; soil firming (using packer equipment) is required in loose, unconsolidated soils. Conversely, compacted subsurface soils restrict water movement and root penetration within the soil and may require plowing prior to planting.
3. **Control erosion and stabilize soils in areas with high erosion potential:** This can be done by planting fast-growing, sterile annual grasses. Annual grasses like wheat grow faster than perennial grasses and thus provide soil stabilization more quickly; they can also help to compete with invasive annual grasses. This technique is often followed by seeding perennial grasses in the next growing season. Mulching with straw or other organic materials also helps to control erosion but is less effective in areas with high rain or wind intensity. It is important to select mulch materials that do not contain invasive species seeds (for example, rice straw is often used since it contains wetland seeds that are not likely to survive in sagebrush habitat).
4. **Revegetation of desired native species:** This may include sagebrush, perennial herbaceous plants, or both, depending on the initial state of the site. Revegetation is usually done by seeding, but transplanting can be a useful alternative in certain contexts.
    - **Seeding:** There are a variety of tools used for seeding. Rangeland seed drills are used to bury seeds, which increases germination success for many perennial grasses. Species with smaller seeds often do better when applied to the surface and pressed in to increase contact with soil. Seeds can also be broadcast from ground-based equipment or aerially (via planes or helicopters), but this increases the potential for seeds to be blown or washed away before they germinate (Figure 1). Mulching seeds with soil or plant litter after aerial seeding can help to prevent this. Seeding should occur just before the rainy season, which varies by location.

Figure 14.1 Aerial seeding of a sagebrush restoration project in Utah

Photo courtesy US Fish and Wildlife Service Mountain Prairie

- **Transplanting:** Where soil stabilization or quick recovery of vegetative structure are required (e.g., for wildlife habitat goals, windbreaks, or aesthetics), transplanting can be a useful alternative to seeding (Figure 2). Certain species also do better from transplants than seeding; there is evidence that after wildfire, sagebrush seedlings have higher survival rates when transplanted than seeded (Grant-Hoffman and Plank 2021). It can take additional time to obtain the plants required for transplanting, which should occur just before the growing season on cool, overcast, windless days.

5. **Rehabilitation:** Technically, active restoration is only possible when site soil and hydrologic characteristics are still capable of supporting original native plant communities. Extensive soil loss, which frequently occurs after fires, can prevent this and requires the use of different plant species (including introduced species) to provide similar structure and function and prevent further degradation. The USGS and DOI Restoration Handbook refers to this as *rehabilitation*, rather than restoration of the original habitat (Pyke et al. 2015). The rehabilitation process follows a similar process to that for active restoration, except revegetation includes different species.

Figure 14.2 Growing sagebrush seedlings for transplant

Photo courtesy Bureau of Land Management

OPERATIONS AND MAINTENANCE

Preventing livestock grazing after restoration is often required to allow vegetation to reach desired density and size before introducing grazing disturbance (Pyke et al. 2017). The length of time required varies by vegetation species and climate (vegetation recovers more quickly in wetter climates), but generally ranges between two and four growing seasons, with additional time required for sites that were burned and broadcast seeded, sites with remaining invasive grasses, and sites with erosive soils.

FACTORS INFLUENCING SITE SUITABILITY

✓ **Cool moist climates:** Sagebrush ecosystems in cool, moist climates are likely to respond well to passive restoration because they are more resistant to invasive annual grasses than hotter, drier areas (Pyke et al. 2017).

- ✓ **Mean annual precipitation of at least 13 in.:** Higher annual precipitation has been found to increase seeding success for perennial grasses (Pyke et al. 2017).
- ✗ **Steep slopes:** Equipment used for seeding cannot operate on steep slopes (greater than 30%) (Pyke et al. 2017). Aerial seeding methods can be used instead.
- ✗ **Stony soil (more than 15% stone cover):** Stones can damage equipment and increase fire risk from sparks created when metal equipment strikes stones (Pyke et al. 2017). Aerial treatment methods can be used in these areas instead of ground-based equipment.
- ✗ **High erosion potential:** Extra care should be taken not to disturb soil in areas with high erosion potential to avoid additional soil loss (Pyke et al. 2017).

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?
Restoration Handbook for Sagebrush Steppe Ecosystems with Emphasis on Greater Sage-Grouse Habitat— Part 1: Concepts for Understanding and Applying Restoration, Part 2: Landscape Level Restoration Decisions, and Part 3: Site Level Restoration Decisions	Guidebook	2015 (Parts 1 and 2), 2017 (Part 3)	USGS	National	Introduction to sagebrush ecosystem structure and function, and in-depth information about planning and implementing passive and active restoration approaches. Includes plant lists.	✓	✓	✓	—
Erosion Risk Management Tool	Online tool	2014	US Department of Agriculture, Forest Service (USFS)	National	Tool to assess the probability of erosion after a prescribed burn in sagebrush ecosystems, based on climate, soil, vegetation, slope, and fire characteristics.	—	✓	—	—
Reseeding Big Sagebrush: Techniques and Issues	Report	2005	USFS	National	Details on seeding big sagebrush, including site evaluation, pretreatment, seed testing and storage, germination, seeding techniques, and postseeding management and monitoring.	✓	✓	✓	—
Prioritizing Restoration of Sagebrush Ecosystems (PReSET)	Software	2021	USGS	National (has been run for Wyoming and work is ongoing to provide applications in other areas)	Decision-support map tool to identify priority sites for sagebrush management based on management priorities for restored or conserved habitats.	—	✓	—	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Climate-Smart Restoration Tool	Online Tool	2019	USFS	Western United States	Identifies geographic areas within which seeds and native plants can be transferred based on current and future climate data.	✓	✓	—	—
Restoration of Sagebrush Ecosystems Class	Training	Offered annually	Bureau of Land Management (BLM), Great Basin Fire Science Exchange	Great Basin	In-person class on sagebrush restoration, including planning, techniques, and monitoring.	✓	✓	✓	—
Bipartisan Infrastructure Law Funding through the Sage-Steppe Ecosystem Restoration Program	Online tool	Covers fiscal years 2022 through 2024	US Fish and Wildlife Service (USFWS)	Western United States	Identifies sagebrush restoration projects by USFWS funded through the Bipartisan Infrastructure Law	—	—	—	✓
Grassland and Sagebrush Conservation Portal	Online tool	Not provided	USFWS	Western United States	Compilation of resources for grassland and sagebrush restoration practitioners, including a web map for priority sagebrush areas, links to existing projects, and data synthesis on invasive annual grasses.	✓	✓	✓	✓
A Sagebrush Conservation Design to Proactively Restore America's Sagebrush Biome	Guidebook	2022	USGS	Western United States	Spatially explicit sagebrush conservation plan to identify priority areas for collaborative conservation.	—	✓	X	X
Sagebrush Conservation Strategy—Challenges to Sagebrush Conservation	Guidebook	2021	USGS	Western United States	Overview of sagebrush ecosystem and dependent wildlife species, plus extensive discussion of causes of sagebrush degradation and strategies to address them. Also includes a chapter on adaptive management and monitoring.	✓	—	✓	—

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Reduced wildfire risk:** Invasive annual grasses that often dominate degraded sagebrush ecosystems are very susceptible to fire and fuel large wildfires. Restoring native plants and removing these invasives reduces wildfire risk (Pyke et al. 2015).
- **Carbon storage and sequestration:** Soil carbon stocks are significantly higher under native sagebrush than under cheatgrass (an invasive annual grass), so sagebrush restoration can increase carbon storage (Austreng et al. 2011).

Social and Economic

- **Jobs:** Active sagebrush restoration supports local jobs. Reducing wildfire risk on sagebrush habitats also reduces risks to nearby land-based jobs such as ranching.
- **Cultural values:** Healthy sagebrush habitat supports traditional livelihoods such as grazing, as well as connection to the land through recreational opportunities.
- **Recreational opportunities:** Sagebrush habitats are used for a variety of recreational activities including camping, off-highway vehicle use, and hunting (ECONorthwest 2014).

Ecological

- **Supports wildlife:** Sagebrush restoration is frequently driven by sage-grouse habitat needs. Research shows that other wildlife species, including mule deer and songbirds (e.g., Brewer's sparrow, green-tailed towhee) also benefit from sagebrush restoration (Stemler 2015).
- **Invasive and nuisance species management:** Removing invasive species (primarily annual grasses such as cheatgrass) and nuisance woody vegetation is a key part of sagebrush restoration.
- **Supports native plants:** Sagebrush restoration aims to enhance native sagebrush and perennial herbaceous plants.

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 sagebrush conservation and restoration are included here.

- **Expense:** Uncertainty about future funding levels for sagebrush management impedes long-term planning and projects (Calzado-Martinez et al. 2023).

- **Capacity:** The geographic scale of sagebrush degradation, particularly invasive grass dominance, overwhelms agency capacity to address the issue (Calzado-Martinez et al. 2023).
- **Public opinion**
- **Conflict with other land uses:** Sagebrush habitats are used for grazing, recreation, and mining and energy; these uses may be temporarily or permanently excluded during restoration (Pyke et al. 2015; Remington et al. 2021).
- **Regulation:** This is especially true for newer techniques, like transplanting, that are required to go through the entire National Environmental Policy Act process rather than a faster categorical exclusion (Calzado-Martinez et al. 2023).
- **Lack of effectiveness data:** Particularly, data identifying which sites are most suitable for restoration (Calzado-Martinez et al. 2023).

Ecological

- **Invasive species:** Invasive plant species including annual grasses dominate degraded sagebrush habitats and are extremely difficult to eradicate (Pyke et al. 2015).
- **Altered fire regimes:** Fire regimes that influence sagebrush habitats are not well-understood and have been altered by human interference, invasives, and climate change. This has caused large-scale conversion from native sagebrush plant communities to fire-prone invasive annual plants (Remington et al. 2021).
- **Climate change:** Rising temperatures and modest increases in precipitation are expected to change drought and moisture availability patterns in sagebrush areas, which could cause additional loss of sagebrush habitats (Remington et al. 2021).
- **Free-roaming equids:** Without active management to reduce population growth, wild horse and burro populations could more than double in four years, exceeding the carrying capacity of rangelands including sagebrush and causing additional ecosystem degradation (Remington et al. 2021).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Five Creeks Rangelands Restoration	Oregon	**BLM,** Harney County Soil and Water District	Mechanical removal of juniper trees, controlled burns, aerial reseeding	~75,000	>2 million	At least 10 years	Heavy grazing in the 1800s changed the plant community, allowing juniper to encroach and dominate. This also changed the fire regime, with many fewer fires in a juniper -dominated system. The project aimed to restore historical sagebrush habitat that would provide forage and habitat for important species, reduce erosion, enhance stream flows, and allow for easier animal movement.	No	Monitoring is underway
Anthro Mountain Greater Sage Grouse Habitat Restoration	Ashley National Forest, UT	USFS	Mechanical removal of pinyon and juniper trees using the "lop and scatter" method to remove the pinyon-juniper overstory without removing sagebrush and other understory species	1573	43,000 (for tree removal only)	1 year	Sage grouse seasonal habitat was being degraded through encroachment of pinyon-juniper. The project was completed to provide winter habitats for the greater sage grouse.	No	This project was a local test of the "lop and scatter" tree removal method, and results helped inform other restoration efforts

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Kelly Hayfields Sagebrush Habitat Restoration	Grand Teton National Park, WY	**National Park Service,** Grand Teton National Park Foundation, Teton Conservation District, **USFWS,** University of Wyoming	Removal of nonnative hay crop, collection and propagation of native seeds on- and off-site, replanting native species, ongoing removal of invasives	4500	400,000 annually (since 2007)	Ongoing (began 2007)	The project was meant to restore historical sagebrush habitat that had been converted to hay fields in the 1800s. The sagebrush areas are important habitat that benefit bison, elk, pronghorn, sage grouse, and songbirds.	No	Various restoration methods have been tested using adaptive management strategies.

Bolding indicates DOI affiliates.

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Built Environments
15. Built Wetlands

DEFINITION

Built wetlands, also known as *constructed*, *artificial*, or *treatment* wetlands, are water treatment systems built with wetland soils and vegetation to mimic the ecological and biophysical processes that improve water quality in natural wetlands (EPA 2023). They are generally shallow channels or ponds with wetland plants into which wastewater or stormwater is directed for treatment (EPA 2000). Built wetlands can be used to treat urban stormwater runoff as well as wastewater (Scholz 2015). They can remove a variety of pollutants including suspended solids, nitrogen, phosphorus, hydrocarbons, and metals (Gelt 1997).

TECHNICAL APPROACH

There are multiple ways to categorize built wetlands. One primary way is by the direction of flow: horizontal or vertical (UN-HABITAT 2008). Both use similar design and construction approaches, with differences in how water moves through the wetland. General steps for creation of a built wetland are outlined as follows.

1. **Excavation:** The project site is excavated and leveled to create a wetland basin that is level or slightly sloped (0.5% to 1%) toward the outflow in horizontal flow wetlands, with berms sufficient to contain rainfall during storms. Horizontal flow wetlands are generally 30–45 cm deep, and vertical wetlands 50–100 cm deep. If soils are highly permeable or if the wetland will be used for wastewater treatment, a liner should be used to prevent infiltration and protect groundwater quality (UN-HABITAT 2008).
2. **Substrate addition:** The basin is filled with a substrate that distributes flow, traps particles, allows vegetation rooting, and supports the microbial community (UN-HABITAT 2008). A variety of substrates can be used, including natural materials (gravel, sand) or artificial and industrial products. Some artificial and industrial products are designed for high hydraulic conductivity and phosphorus sorption capacity and may be useful when nutrient removal is required (Wu et al. 2015).
3. **Inlet and outlet construction:** Inlet and outlet structures are placed to allow effluent to flow into the built wetland and treated water to flow out of the wetland. There are a variety of inlet structures, including perforated pipes, channels, and gabions (cages filled with rocks). These structures should be placed so that water flows evenly throughout the entire wetland, rather than creating “dead zones” that are not in the flow path; vertical flow wetlands often require a network of pipes or channels to distribute the water over the wetland surface. Outlet structures are usually drainpipes or weirs that can be adjusted to set the water level in the wetland (UN-HABITAT 2008).

4. **Vegetation:** Vegetation is established by transplanting seedlings or plants or by broadcasting seeds (UN-HABITAT 2008). Emergent wetland plants are primarily used in constructed wetlands; in North America, the most used species are *Typha latifolia* and other *Typha* species (Figure 1). Because built wetlands are designed to remove pollutants, it is important to consider the plants' tolerance of the toxins and nutrients in wastewater, as well as their ability to remove pollutants (Wu et al. 2015).
5. **Water:** At first, clean water is introduced into the system to support plant growth. Once plants are established, increasing amounts of wastewater or stormwater effluent can be introduced. Wastewater needs to undergo primary treatment (separating suspended matter through settling) before the effluent is introduced into a built wetland (UN-HABITAT 2008).

OPERATIONS AND MAINTENANCE

Once established, built wetlands are relatively low-maintenance (UN-HABITAT 2008). Regularly required maintenance includes checking inlets and outlets, clearing debris and accu-

Figure 15.1 A stormwater treatment wetland in Apex, NC

Photo courtesy NC Wetlands

mulated sediment (especially if it blocks flows), and removing nuisance and invasive species (EPA 2000). Adjusting water levels and maintaining berms may be needed periodically. Because built wetlands are water treatment systems, water should be sampled and tested regularly to assess treatment efficacy (UN-HABITAT 2008).

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Historic, degraded wetlands without a water source:** Built wetlands can be used as a restoration approach for historic wetlands that no longer have a reliable water source (EPA 2000).
- ✓ **Medium- to fine-textured soils:** These types of soils are highly suitable for vegetation establishment, water retention, and pollutant trapping (MassDEP Wetlands Program 2008).
- ✗ **In a floodplain, floodway, or existing wetland complex:** Built wetlands should generally be sited outside of floodplain, floodway, or existing wetland areas to avoid degrading natural aquatic resources (EPA 2000).
- ✗ **Highly permeable soils:** Soils that allow rapid infiltration can cause groundwater contamination and make it difficult to create a hydrologic regime suitable for wetland vegetation (EPA 2000). Impermeable liners can be used to prevent infiltration if needed.
- ✗ **Shallow bedrock:** Basin excavation may be cost-prohibitive if bedrock is near the surface (MassDEP Wetlands Program 2008).
- ✗ **Discharge to cold-water fishery area:** Treated effluent may still have higher nutrient levels or temperatures that can disrupt cold-water fish habitat (MassDEP Wetlands Program 2008).

TOOLS, TRAINING, AND RESOURCES FOR PLANNING AND IMPLEMENTATION

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Resource Includes: Site Selection?	Resource Includes: Monitoring Guidance?	Resource Includes: Example Projects?
Constructed Wetlands Manual	Guidebook	2008	United Nations Human Settlements Programme	Global	Overview of built wetlands design and construction process	✓	✓	✓	✓
Manual: Constructed Wetlands Treatment of Municipal Wastewaters	Guidebook	2000	US Environmental Protection Agency	National	Explains how built wetlands function, project design, construction, operations, and monitoring	✓	✓	✓	✓
Wetland Construction: Principles, Planning, and Design	Course	N/A	Rutgers University	National	Four-day online course on planning, designing, and constructing a functional wetland	✓	✓	—	—

GRAY INFRASTRUCTURE ALTERNATIVES

Built wetlands can be an alternative to gray stormwater treatment and sewage treatment facilities. The ability of a built wetland 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 built wetlands. See the gray infrastructure alternative tables in Section 1 for a comparison of built wetlands to these alternatives.

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Reduced flooding:** Built wetlands temporarily store water and can help to attenuate peak flows during storms (MassDEP Wetlands Program 2008).

- **Drought mitigation:** Built wetlands can provide effluent that meets water quality standards for reclaimed water, increasing water supplies during drought (Rousseau et al. 2008).

Social and Economic

- **Aesthetics:** Built wetlands have more aesthetic value than gray infrastructure alternatives (e.g., wastewater treatment plants) (Minnesota Pollution Control Agency 2023).
- **Recreational opportunities:** Built wetlands can provide opportunities for birdwatching, hiking, and other outdoor recreation (Minnesota Pollution Control Agency 2023). However, not all built wetlands are open to the public.

Ecological

- **Improved water quality:** Built wetlands are highly effective in trapping sediment and pollutants associated with sediment and can remove some nitrogen and phosphorus (Minnesota Pollution Control Agency 2023).
- **Supports wildlife:** Built wetlands are valuable for wildlife that use wetland habitats, including birds, reptiles, and amphibians (Minnesota Pollution Control Agency 2023).

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 built wetlands are included here.

- **Expense**
- **Capacity**
- **Public opinion:** In particular, communities are often concerned about the potential for built wetlands to create breeding habitat for mosquitoes (MassDEP Wetlands Program 2008).
- **Conflict with other land uses:** Built wetlands require more land than gray infrastructure alternatives, so they have greater potential for conflict with other land uses.
- **Regulation:** Built wetlands are not functionally equivalent to natural or restored wetlands, so they generally cannot be used for wetland mitigation.
- **Lack of effectiveness data**

Ecological

- **Adverse wildlife effects:** Built wetlands may intercept breeding amphibians trying to reach vernal pools (MassDEP Wetlands Program 2008).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Huie Constructed Wetlands	Clayton County, GA	Clayton County Water Authority	Horizontal flow wetlands	532	30 million (Wysocky 2021)	Constructed in four phases between 2004 and 2010 (Hall 2010)	263 wetland cells treat up to 17.4 million gallons of water per day from the water treatment facility and discharge the filtered water into two reservoirs (Wysocky 2021).	Drought (almost 100% of daily water use is returned to waterways via the treatment wetlands) (Hall 2010).	Built wetlands are more cost-efficient and use less land than the previous system, which used pipes and sprinklers to distribute treated water over timberland (Wysocky 2021).
Demonstration Urban Storm Water Treatment Marsh	San Francisco, CA	Association of Bay Area Governments	Built wetland consisting of multiple ponds, shallow basins, and marshes.	~30	Not available	Constructed in early 1980s; specific duration not available	Constructed wetland built in degraded wetland that had been diked and filled. Water was diverted from an urban creek channel into the built wetland for treatment (Wetzig 1995).	No	Dense cattail growth restricted flow, requiring modification of the weir to restore flow (Wetzig 1995).

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Harbor Brook Constructed Wetlands Pilot Treatment System	Syracuse, NY	Onondaga County Department of Water Environment Protection	Horizontal flow wetland, vertical down flow wetland, and “floating wetland island”	34	4.5 million	3 years (from contracting to completion of construction)	Multiple types of built wetlands treat effluent from a combined sewer overflow (14.9 million gallons treated per year) and discharge into Harbor Brook	No	Pilot project was designed to test the effectiveness of different types of built wetlands; knowledge gained will be used to inform larger built wetland projects in the same area.
South Los Angeles Wetland Park	Los Angeles, CA	City of Los Angeles	Stormwater runoff is pretreated to remove debris, gasoline, etc. and circulated through built wetland pools.	4.5 acres of built wetlands and 4.5 acres of upland habitat	12.4 million	Completed in 2011; specific duration not available	Wetland park with riparian and marsh habitat on a former brownfield site treats urban runoff from a 525 acre watershed.	No	Supplemental water is needed to maintain wetland habitats during droughts. Missed opportunities to connect with local community for recreation and education (e.g., lack of signs in Spanish, no restrooms on site).

Bolding indicates DOI affiliates.

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Built Environments
16. Urban Greening

DEFINITION

Urban greening is a general term used to describe efforts to renature urban areas by installing various types of green infrastructure. These revegetation strategies are often implemented with climate resilience goals in mind, but are also often cited as a way to increase local residents' mental and physical health (García-Lamarca et al. 2022). This strategy focuses on three different forms of urban greening: urban forestry, green roofs, and pollinator gardens.

Urban forestry is an "integrated concept defined as the art, science, and technology of managing trees and forest resources in and around community ecosystems for the psychological, sociological, aesthetic, economic, and environmental benefits trees provide society" (Konijnendjik and Randrup 2004). *Reforestation* refers to reestablishing trees on lands that were recently covered by forest but experienced a disturbance, such as wildfire, timber harvest, or wind effects. *Afforestation* refers to the establishment of trees in areas that have not recently been covered in forests. Since there is no agreed-upon timeline when referring to reforestation versus afforestation and they are often used interchangeably, the term *urban reforestation* is used here to refer to both reforestation and afforestation, (IPCC 1998). Urban reforestation is a nature-based solution in which trees are planted in urban areas to subdue the effects of climate change and provide cobenefits to the environment and people (Ogunbode and Asifat 2021).

Green roofs, also known as *vegetated roofs* or *living roofs*, are defined by the vegetated layer growing on top of a rooftop (Figure 1; GSA 2021; EPA 2014). There are two different types of green roofs: *extensive*, in which lighter plants are planted and little maintenance is required; and *intensive*, which are similar to traditional gardens or parks and can handle most plant types, but need more structural support, higher initial investment, irrigation, and continued maintenance compared to extensive green roofs (EPA 2008). *Semi-intensive* green roofs represent a hybrid of both types (EPA 2021). Green roofs have layers that each perform different purposes, including plant growth, waterproofing, and structural support (EPA 2014).

Pollinator gardens are efforts to create green spaces filled with native plants that are attractive to pollinators. These gardens are typically installed to help support local pollinators, which globally have been declining due to pesticides, disease, and habitat loss. These gardens are designed to provide resources that pollinators need, including food sources (nectar and pollen), nesting sites, and larval host plants (Majewska and Altizer 2018).

TECHNICAL APPROACH

Technical approaches differ for the three urban greening strategies included in this strategy:

- **Urban forestry:** The Vibrant Cities Lab, a partnership between the US Department of Agriculture Forest Service (USFS), American Forests, and National Association of

Figure 16.1 Green roof in Ohio

Photo courtesy Dan Keck

Regional Council, outlines a seven-step approach to setting up urban forestry projects and programs (Vibrant Cities Lab 2017b).

1. **Assess:** The first step is to assess what the tree canopy looks like within the project area, including street trees outside of established parks. This can be achieved using the i-Tree Canopy application or with other available lidar or remote sensing data (i-Tree n.d.). The USFS has put together a five-step Urban Tree Canopy Assessment that will aid in the process of assessing and monitoring the tree canopy to ensure the proper management decisions are being made (Hermansen-Baez 2019).
2. **Prioritize:** It is important to consider "human health, economic development, water quality, air quality, public safety, equity, transportation, education, and city planning" when deciding which urban public lands should be invested in. A geographic information system is an important tool in this process because multiple different layers of geospatial data can be overlaid to see areas that could benefit most from urban reforestation intervention.

Figure 16.2 Tree planting in South Los Angeles, CA

Photo courtesy Santa Monica Mountains National Recreation Area

3. **Organize:** The next step is engaging the local community, municipalities, parks, and other agencies. Engaging the public can also aid in equity goals. Within the organization phase, it is important to make the case and communicate the goals for the project in a way that brings people into the conversation (TNC 2015; Vibrant Cities Lab 2017).

4. **Plan:** There are comprehensive guides that illustrate the necessary steps that go into an urban forestry plan (Vibrant Cities Lab 2017). It is important to remember what goals the project seeks to achieve with its implementation. These goals can include climate, community, and infrastructure aims dependent on the needs of the region (Kimball et al. 2014).

5. **Build:** This step refers to implementing the plan, specifically tree planting (reforestation) (Figure 2). At this stage, it is a good idea to contact local or state foresters to understand what species will be best for the site, community, and ecology (Vibrant Cities Lab 2017b). Invasive trees are commonly used as street trees and, in some cases, can negatively impact the local ecosystem (Dickie et al. 2013).

6. **Protect:** Possible risks that may need to be mitigated include flooding, fire, pests, disease, invasive species, and climate change. Ensure that the budget will allow for risk mitigation efforts. (Vibrant Cities Lab 2017b).

- **Green Roofs:** There are three primary steps for a green roof installation project.

  1. **Green roof type:** After determining the site for the green roof, the next step is to decide on installing an extensive or intensive green roof. This will depend on the initial investment, maintenance capacities, and the project's goals as a result of the installation (EPA 2008).

  2. **Vegetation:** Once the green roof type is selected, it is essential to decide on the vegetation, which will depend on the roof type, building design, climate, sunlight, irrigation ability, and expected use of the green roof (EPA 2008). For extensive green roofs, the report *Selecting Plants for Extensive Green Roofs in the United States* is a helpful resource for selecting vegetation types; for intensive green roofs, there are many more options (Getter and Rowe 2008, EPA 2008).

  3. **Installation:** Multiple layers are included in green roofs underneath the vegetative layer. These layers include, from the top down, a growing medium, filter membrane, drainage layer, root barrier, thermal insulation, vapor barrier, and structural support (EPA 2014). The growing medium is typically 3 to 6 in. deep for extensive and 6 to 48 in. deep for intensive green roofs. It provides space for the plant's roots and is typically a combination of organic and inorganic materials. The filter membrane prevents the growing media from clogging the drainage layer. The drainage layer removes excess moisture and water from the root zone and can be a variety of thicknesses depending on the vegetation type. The root barrier is meant to protect the water-tight barrier from being infiltrated by the roots. The thermal or insulation layer is used to keep mildew out of the building. The vapor barrier (waterproofing layer) is designed to prevent water damage through the structural building layer; some green roofs will have an additional leak detection system. Lastly, the structural layer is the foundation of the green roof (DOEE n.d., EPA 2014).

     It is possible to intentionally install green roofs with plants that attract and support pollinators, creating a combination green roof and pollinator garden (Howell et al. 2017). For more information on pollinator gardens, see the following section.

- **Pollinator gardens**: Installing pollinator gardens does not take a lot of technical expertise, and the major technical decision required is deciding which plants to include. There are numerous regional native plant guides available that help gardeners select appropriate plants for their geographic region (e.g., the National Park Service (NPS) Ecoregional Planting Guide Cards). Existing guides help gardeners select plants that offer a diverse array of pollen and nectar as well as reproductive resources for pollinators (Majewska and Altizer 2018). The intended garden site must also be appropriately prepared before planting occurs. This includes eliminating existing vegetation, suppressing competition from seeds in the soil, sod removal, smothering, tilling, and appropriate herbicide application. Additional tips for making the garden most productive for pollinators include clustering plants of the same species for efficient foraging and leaving some bare soil available for ground-nesting insect pollinators (USDA 2017).

OPERATIONS AND MAINTENANCE

Operations and maintenance differ for the three urban greening strategies included.

- **Urban forestry**: Monitoring an urban forestry project is crucial to ensure that trees grow properly, risks are being appropriately managed, and the community is engaged. Ensure there is staff dedicated to the maintenance and monitoring of the trees and that they are equipped with the proper tools. Tree maintenance can cost $15-–$81 per tree per year (NOAA 2020). Community volunteers and stewardship organizations can be engaged to aid in monitoring and maintenance efforts (Vibrant Cities Lab 2017b).
- **Green roofs:** Maintenance requirements vary based on the roof type; extensive roofs require much less maintenance than intensive roofs. In general, using low-maintenance vegetation is typically best. Roof inspections should be done twice per year to ensure there are no leakage, structural issues, or drainage problems. During this inspection, it is also essential to check for invasive species and overgrowth. More regularly, the roof may need to be watered and inspected for dead or dying vegetation (DOEE n.d.).
- **Pollinator gardens:** Maintaining a pollinator garden is no different than maintaining any other garden. Maintenance efforts are typically relatively little, including weed removal, pest control, pruning, fertilizing, and watering (Majewska and Altizer 2018). It is important to avoid using pesticides and insecticides for pest control, as even sublethal doses can affect insect pollinator foraging and nesting behavior (USDA 2017).

FACTORS INFLUENCING SITE SUITABILITY

Urban Forestry

- ✓ **Hardiness zone:** Growers can use the hardiness zone of an area to determine which plants or trees would have success (USDA 2012).
- ✓ **Soil volume, composition, and depth:** Adequate soil structure is critical for site suitability for urban trees. Each tree will have different soil requirements, but in general degraded and compact soil will likely not be the best conditions for adequate tree growth (Arango 2015).
- ✗ **Wind:** It is important to ensure that the trees are adapted to the wind in the area, so they will not be blown over. If trees are adapted to a specific site, they are more resistant to winds (Ogunbode and Asifat 2021).
- ✗ **Salt:** In urban areas where salt is either used for deicing, there is sea spray, or there are generally salty soils, it is important to plant saline-tolerant trees. Trees that are not saline-tolerant can have adverse reactions to high salinity in soils, such as diminished growth and appearance or death (Fox and Koci 2022).

- ✗ **Other trees:** Too many trees in one area will lead to disrupted tree growth (Price 2003).
- ✗ **Overhead wires, lights, and signs:** The distance to powerlines and other overhead obstructions is critical when planting urban trees, specifically street trees. Knowing the tree's height at its tallest is essential to ensure it will not impede on or damage any infrastructure. For powerlines specifically, "within 6 feet the tree should be less than 25 feet tall, but planting isn't recommended; from 6-40 feet the tree should be 10 feet shorter than the wire or the canopy should be less than twice the distance to the wire; and over 40 feet any tree can be planted (Vibrant Cities Lab 2017b)."
- ✗ **Underground utilities:** Trees need room to ensure their roots can grow properly, so it is essential to know where underground utilities such as electric, gas, water, and sewers are located before planting (International Society of Arboriculture 2021).
- ✗ **Adjacent buildings:** Each tree will have a different canopy structure, and based on the canopy structure, one can determine how close the tree can be to a nearby building (i-Trees 2021).
- ✗ **Rooting space:** Because of the spatial limitations of cities and urban areas, finding sites that accommodate tree rooting space can be challenging (Pataki et al. 2021).

Green Roofs:

- ✓ **Built-up urban centers:** Areas in cities that are especially dense with buildings are good sites for green roofs because of the limited space for vegetation elsewhere and the extensive impervious surface coverage (EPA 2008).
- ✓ **Roof size:** Stakeholders will often want green roofs to be implemented on larger roofs to get the most benefits; larger roofs are typically found on low- to midrise buildings (EPA 2008).
- ✓ **Roof type—concrete:** It is easier to add a green roof to roofs that already have a concrete structure (EPA 2008).
- ✓ **New building:** Green roofs are usually easier to install in new buildings because they can be designed as part of the architecture (EPA 2008).
- ✗ **Roof type—steel:** Steel roofs require more intervention and cost to install a green roof (EPA 2008).
- ✗ **Slope:** Sloped roofs are more challenging to install green roofs on, but they can typically be done with extensive green roofs (EPA 2008). Slopes for green roofs can be up to 30%; beyond that, they are typically defined as *green walls* (DOEE n.d.)
- ✗ **Climate:** It is important to consider the local climate when considering vegetation types (EPA 2008).

Pollinator Gardens:

- ✓ **Location:** As long as soil and water are available, pollinator gardens can be planted almost anywhere. However, appropriate plants should be selected based on geographic region and desired pollinators.

TOOLS, TRAINING, AND RESOURCES FOR PLANNING AND IMPLEMENTATION

Urban Forestry

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Urban Forestry Toolkit	Toolkit/ website	Not provided	Vibrant Cities Lab (USFS, American Forests, and the National Association of Regional Councils)	National	Provides a more user-friendly adaptation of The Sustainable Urban Forest: A Step-by-Step Approach (Leff 2016). This is a full-service resource for all the guides, case studies, and research needed for an urban forestry project.	✓	✓	✓	✓
The Sustainable Urban Forest: A Step-by-Step Approach	Guidebook	2016	USFS and Davey Institute	National	Provides a detailed approach to managing forests in the urban setting.	✓	✓	✓	✓
i-Trees	Software	2006	USFS	National	Software that provides tree benefit estimation science through various tools and support.	✓	—	✓	—
Urban Tree Canopy Assessment	Report	2019	USFS	National	Overview of the process of urban tree canopy assessment, including best practices and additional resources.	✓	✓	✓	✓
Tree Planting Campaign Guide	Guidebook	2022	Green Infrastructure Center and USFS	National	Provides guidance on implementing urban tree planting projects from start to finish.	✓	✓	✓	✓
Forests in Cities	Resource library	2019	Natural Areas Conservancy	National	Resource library that provides managers with best practices for managing forests within urban areas as opposed to street trees or landscaped parks.	✓	—	✓	✓

Urban Forestry

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Trees and Health App	Website		Portland State University, Sustaining Urban Places Research Lab, USFS, PlanIT GEO	Albuquerque, NM; Atlanta, GA; Baltimore, MD; Cincinnati, OH; Denver, CO; Houston, TX; Minneapolis, MN; Orlando, FL; Phoenix, AZ; Pittsburgh, PA; Portland, OR; Sacramento, CA; Tampa, FL; Treasure Valley, ID	For 13 cities, this web-based app provides information to allow managers to assess, prioritize, and plan urban forestry projects.	✓	✓	✓	✓
Urban Forest Assessment Resource Guide	Guidebook	2013	American Forests	National	A guide to help assess the urban canopy/street trees within a project area. Provides external sources to help with assessment, management, and modeling.	✓	—	✓	—
Urban Forest Management Plan Toolkit	Website	2016	California Urban Forest Council, USFS, California Department of Forestry and Fire Protection	Designed for California but most of the information is more broadly applicable	This tool kit provides information on developing an urban forest management plan.	✓	✓	✓	✓
Choosing Suitable Trees for Urban and Suburban Sites	Book Chapter	2007	The University of Florida University of Florida's Institute of Food and Agricultural Sciences Extension	Designed for Florida, but most of the information is more broadly applicable	This chapter provides in-depth specifications for deciding what tree species to plant. It does not include a species list but explains what to look for at the site to determine what species to consider.	✓	—	—	—

Urban Forestry

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
USDA Plant Hardiness Zone Map	Map	2012	USDA	National	This interactive map provides information on plant hardiness zone, informing managers about what species to plant.	✓	—	—	—
Urban Watershed: Urban Tree Planting Guide	Guidebook	2016	Center for Watershed Protection	National	This manual helps managers determine the tree planting specifications for an urban reforestation project.	✓	—	✓	✓

Green Roofs

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Green Roof Toolkit	Guidebook	2018	Government of the District of Columbia, Department of Energy and Environment	National	This toolkit provides basic information about green roofs, their benefits, installation considerations, and maintenance needs.	✓	—	✓	—
Design Guidelines and Maintenance Manual for Green Roofs in the Semi-Arid and Arid West	Guidebook	2010	Green Roofs for Healthy Cities, City and County of Denver, Environmental Protection Agency Region 8, Urban Drainage and Flood Control District, Colorado State University	Arid Western US states	This guide provides information on designing and maintaining green roofs in arid western states. It provides information on when certain types of green roofs are most appropriate and their different benefits	✓	—	✓	✓
A Designer's Guide to Small-Scale Retro-fit Green Roof Planning, Design, and Implementation	Guidebook	2013	Kansas State University	National	This guide provides information on how to implement smaller green roofs.	✓	—	✓	—
Green Roofs on Historic Buildings	Website	Not provided	NPS	National	This webpage provides information on how to implement green roofs on historic buildings, specifically within the NPS.	✓	—	✓	✓
Selecting Plants for Extensive Green Roofs in the United States	Guidebook	2015	Michigan State University	National	This guide provides information on what plants have been tested for extensive green roofs in different states.	✓	—	✓	—

Pollinator Gardens

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Pollinator Gardens Design Guide	Guidebook	2017	USDA Natural Resources Conservation Service	National	Tips for how to plant a successful pollinator garden. Includes pollinator garden designs for various site conditions.	✓	—	—	✓
Ecoregional Planting Guides	Guidebook	n.d.	Pollinator Partnership: NAPPC, US Forest Service, Bureau of Land Management, Plant Conservation Alliance, Natural Resources Conservation Service, US Geological Survey, National Association of Conservation Districts	National (individualized guides for each ecoregion of the United States)	Individualized guidebooks for each US ecoregion detailing the pollinators and plants appropriate for pollinator gardens in that region.	✓	—	—	—
Ecoregional Planting Guide Cards	Guidebook	n.d.	NPS	National (individualized factsheets for each ecoregion of the United States)	Individualized guidance for each US ecoregion detailing the plants appropriate for pollinator gardens in that region.	✓	—	—	—
Pollinator-Friendly Best Management Practices for Federal Lands	Guidebook	2015	Pollinator Health Task Force	National	This guidebook is an overview of best practices to promote healthy pollinator populations on federal lands. It is not specific to pollinator garden creation, but includes information that is helpful to those creating pollinator-friendly habitat.	✓	✓	—	—

GRAY INFRASTRUCTURE ALTERNATIVES

- **Urban forestry:** Urban forestry can be an alternative to gray infrastructure approaches that reduce the effects of urban runoff (stormwater drainage system) and urban heat (shade structures). The ability of an urban forestry 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 urban forestry. See the gray infrastructure alternative tables in Section 1 for a comparison of urban forestry to these alternatives.
- **Green roofs:** Green roofs can be an alternative to cool roof coatings, which are also designed to reduce urban heat and energy use. The ability of a green roof project to replace or supplement this gray infrastructure approach 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 a green roof. See the gray infrastructure alternative tables in Section 1 for a comparison of green roofs to this alternative.

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Heat mitigation:**
  - **Urban forestry:** Trees reduce heat islands as a result of shading and the evapotranspiration of water from their leaves (Ennos 2012). *Heat islands* are areas with structures such as buildings and roads that absorb and reemit the sun's heat. Heat islands lead to an increase in energy consumption, emissions of air pollutants and greenhouse gases, compromised human health, and poorer water quality. Adding greenery, specifically trees, can significantly decrease the impacts of urban heat islands (EPA 2014).
  - **Green Roofs:** Green roofs can reduce urban heat through shading and evapotranspiration (EPA 2008, GSA 2021). Green roofs can stay 40°F to 50°F cooler than conventional roofs (DOEE 2018)
- **Improved air quality:**
  - **Urban forestry:** Trees can reduce pollution because of their cooling effects and removing pollutants from the air. Trees' stomata (leaf pores) can directly remove gaseous pollutants from the air. Trees can also temporarily contain particulates on the surfaces of leaves and bark, but they will reenter the environment either in the air or soil (NPS 2022). In the Northeast and Midwest regions of the United States, the removal of air pollutants was valued at an estimated $1.36 billion (NMSFA 2022).

- **Green roofs:** Green roofs create more vegetation in the urban environment, which removes pollution and greenhouse gases (GHGs) as a result of carbon sequestration and storage. The reduction in energy use also leads to reduced GHG emissions. Another GHG reduction is provided from the cooling effect, which helps reduce ground-level ozone caused by increased urban temperatures (EPA 2008).

- **Carbon storage and sequestration:**
  - **Urban forestry:** One benefit of trees is their ability to absorb and store carbon dioxide. Though urban forests in the United States account for only 3% of the country's forests, their carbon storage can help cities reach their emission reduction goals (Pregitzer et al. 2021). In the Northeast and Midwest regions of the United States, the sequestration of carbon in urban forests was valued at $1.06 billion (NMSFA 2022).
- **Reduced flooding:**
  - **Urban forestry:** The installation of urban trees reduces flood risk (Leff 2016). Trees distribute water due to the canopy cover, which decreases rapid water rise. Trees also provide porous soils, so water can more easily infiltrate (Trees Energy Conservation 2019).
  - **Green roofs:** Green roofs can reduce and slow stormwater runoff because of the vegetation's ability to use and retain water (GSA 2021). A study of an agricultural green roof in New York City found that the green roof retained 2.3 times more stormwater when compared to urban forests (Harada and Whitlow 2020).
  - **Pollinator gardens:** Pollinator gardens can allow for increased infiltration of stormwater for localized flood reduction benefits (APA 2021)

Social and Economic

- **Jobs:**
  - **Urban forestry:** Urban reforestation provides local jobs (Vibrant Cities Lab 2017b). In the Northeast and Midwest regions of the United States, urban forestry employed more than 357,200 people with a payroll of ~$16.05 billion (NMSFA 2022).
  - **Green roofs:** The green roofing industry continues to provide stable employment for both installation and maintenance (DOEE 2018).
- **Mental health and well-being:**
  - **Urban forestry:** Numerous studies correlate physical and mental health with green spaces. However, there is still a need for studies to quantify the influence of urban trees on human health (Pataki et al. 2021). There are also correlations between natural areas and stress reduction, which leads to a more positive emotional state (Ulrich et al. 1991).

  - **Green roofs:** Cooler temperatures benefit human health and comfort. Green roofs also provide spaces for people to connect with nature in urban areas, which has proven health benefits (EPA 2008).
  - **Pollinator gardens:** Pollinator gardens provide access to nature in urban areas, which has been known to be associated with mental health benefits (APA 2021)
- **Recreational opportunities:**
  - **Urban forestry:** Urban greenspace and forests encourage people to recreate and exercise (Lupp et al. 2016).
- **Aesthetics:**
  - **Urban forestry:** The aesthetic value of trees, although difficult to quantify, is a crucial benefit of urban trees (Price 2003).
  - **Green roofs:** Green roofs provide positive aesthetics for those who enjoy them (Skabelund and Brokesh 2013).
  - **Pollinator gardens:** Pollinator gardens are centered on flowering plants, providing aesthetic benefits (APA 2021)
- **Increased property values:**
  - **Urban forestry:** Home prices increase if a tree is on the premises (NC State 2022).
  - **Green roofs:** The addition of a green roof can increase the value of the building (DOEE 2018).
- **Wind and noise reduction:**
  - **Urban forestry:** Urban trees and parks can help reduce wind and noise by acting as barriers (Chiesura 2004).
- **Crime reduction:**
  - **Urban forestry:** Numerous case studies show a correlation between increased canopy cover and reduced crime (Vibrant Cities Lab 2017a, Kuo and Sullivan 2008). However, this relationship has been debated in the academic literature (e.g., Troy et al. 2012; Bogar et al. 2015).
- **Reduced energy use:**
  - **Urban forestry:** Urban trees can help reduce energy use by helping to shade buildings, cooling air temperatures, and altering wind speeds around buildings. In the United States, residential energy savings by trees has been valued at $7.8 billion annually (Nowak et al. 2017).
  - **Green roofs:** Because of the water storage capabilities of green roofs, they can provide insulation in both the summer and winter by reducing temperature fluctuations (EPA 2008). In the summer, green roofs can cool the air through evapotranspiration (EPA 2014). Green roofs can lower the cost of energy by reducing heating and cooling needs for buildings (Tolderlund 2010).

- **Food security:**
  - **Green roofs:** Green roofs can be used to house community gardens, greenhouses, or rooftop farms, which can contribute to increased food security (Harada and Whitlow 2020).
- **Reduced or avoided costs:**
  - **Green roofs:** Green roofs typically last twice as long as conventional roofs (GSA 2021).

Ecological

- **Reduced runoff:**
  - **Urban forestry:** Tree canopies can reduce both the temperature and volume of stormwater runoff because of rainfall interception from leaves, porous soils, and shading over the pavement (Kimball et al. 2014). In the Northeast and Midwest regions of the United States, an estimated $635 million was valued from stormwater reduction (NMSFA 2022).
- **Supports wildlife:**
  - **Urban forestry:** Additional trees within urban areas can produce a more robust pollinator population (species dependent on location). More pollinators can contribute to a healthier ecosystem and increased biodiversity (Baldock et al. 2015).
  - **Pollinator gardens:** Pollinator gardens are created to provide food, habitat, and reproductive resources for pollinator species (APA 2021).
- **Enhanced biodiversity:**
  - **Urban forestry:** Urban trees can create additional habitats and resources for wildlife, positively impacting the ecosystem (Mexia et al. 2018).
  - **Green roofs:** Green roofs can provide habitat for plants, insects, and birds in urban environments (GSA 2021; DOEE 2018). Green roofs can also provide effective corridors for these various species and provide critical habitats for pollinators (Harada and Whitlow 2020).

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 urban greening are included here.

- **Expense:**
  - **Green roofs:** Green roofs are more expensive than conventional roofs. Intensive green roofs typically cost around $40 more per square foot, and extensive green

roofs generally cost around $10 to $30 more per square foot than conventional roofs (DOEE 2018). There is also a significant maintenance cost, especially with intensive green roofs (Salter 2021).

- **Capacity**
- **Public opinion**
- **Conflict with other land uses:**
    - **Urban forestry:** Urban areas are limited in their capacity to implement reforestation projects because much of the community space is already allocated toward initiatives like affordable housing (Pataki et al. 2021). Some activist groups are promoting a "Trees and" approach for cities to follow, allowing both initiatives to be achieved through conscious planning (Ionescu 2022).
- **Regulation**
- **Lack of effectiveness data**

Economic

- **Urban forestry:**
    - **Maintenance:** In 2005, the cost of maintaining urban trees was estimated between $12.87 to $65 annually per tree. It is crucial to factor maintenance costs into a project budget to ensure trees are properly maintained. However, though maintenance expenditures can be high, the benefits reported from the same cost-benefit analysis stated that for every dollar spent, the return on investment ranged from $1.37 to $3.09 (McPherson et al. 2005).
    - **Damage to infrastructure:** Tree roots often damage sidewalks, which can lead to liability claims. Falling trees can also damage homes, cars, lighting, sewers, and phone or electrical wires. Damage can be avoided with proper site suitability analyses and site preparation (Trees Energy Conservation 2019).
    - **Cost of improper planting:** If trees are planted or maintained incorrectly and die, they can be an eyesore, imply a lack of investment in the community, and have significant financial costs (Roman et al. 2021).
- **Green roofs:**
    - **Potential leakage:** There is a potential for the roots to penetrate the waterproof layer, which causes leaks, potentially leading to structural and property damage. Finding the leak can also be a challenge because of the complexity of the roof (Salter 2021).

Community

- **Urban forestry:**
    - **Safety concerns of large wooded areas:** Some people may not want a large wooded area close to them because of their associated potential danger (Pataki et

al. 2021). A case study in Washington, DC, showed that automobile-related crimes were more common in areas with trees as a result of more visual ground coverage (Vibrant Cities Lab 2017a).

- **Barriers to access:** Green spaces are less accessible for low-income communities of color as compared to affluent, white neighborhoods. In Los Angeles, this disparity is evident in the tree canopy cover. The tree canopy cover is 55% in an affluent neighborhood, compared to 10% in a low-income neighborhood (Kunsch and Parks 2021). Acknowledging and combating these disparities in urban reforestation projects' development, implementation, and maintenance stages is essential.
- **Lack of community involvement:** In an example in Detroit, the city tried to implement an urban tree project, but many residents did not want trees on their property. The residents felt the city was not involving them in the conversations, and communities of color did not have a seat at the decision-making table. It is important to ensure all stakeholders have a place in the discussion in regard to any environmental justice or community environmental initiative (Mock 2019).

- **Green roofs:**
  - **Fire hazard:** Green roofs can become a fire hazard when dry, so it is essential to use fire-resistant plants, like sedums, and construct a fire break if the vegetation is expected to dry out in the summer (EPA 2008).

Ecological

- **Urban forestry:**
  - **Spread of pests:** Urban trees are often more susceptible to pests because of the proximity to human activities that aid in the spread of forest pests. Pest management can cost agencies and municipalities millions of dollars. It is important not to plant a single species and to diversify urban trees to limit the spread and impact of forest pests (Hudgins et al. 2022).
  - **Nonnative invasive trees:** Often, trees used as street trees or for urban forests are invasive or nonnative, and this can result in disturbance to the ecosystem (Roman et al. 2021).
- **Pollinator gardens:**
  - **Pesticides:** One of the major threats to insect pollinator populations is harmful pesticides. Even if pesticides aren't used within a pollinator garden, their use in nearby areas can negatively affect pollinators that visit the garden (Xerces Society, n.d.).

EXAMPLE PROJECTS

Urban Forestry

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Providence Neighborhood Planting Program	Providence, RI	City of Providence, Rhode Island Parks Department, Providence Neighborhood Planting Program	Community urban tree planting	20.6 mi²	Not provided	Ongoing (began 1988)	The Providence Neighborhood Planting Program aims to engage the community by planting trees in lower-income areas with less canopy cover. (American Forests 2023).	Store carbon, cool the city	Working with anchor institutions like schools can have a larger impact than working directly with individuals (American Forests 2023).
Million Trees NYC	New York City	City of New York Department of Parks and Recreations	Municipality planted 70% of trees in public spaces and relied on private owners to plant 30% of the trees	~300 mi²	$400 million	2007–2015	This project was in partnership with New York Restoration Project, and the goal was to plant 1 million trees throughout NYC. This was achieved in 2015.	Carbon sequestration, reducing energy use, reducing CO2 emissions, improving air and water quality, lowering summer air temperature	Developing a program for community members to lead tree stewardship efforts in their area helped with the maintenance and education efforts across such an expansive area (New York City Global Partners 2013).
Madrid Reforesta: Bosque Metropolitano	Madrid, Spain	Área de Gobierno de Desarrollo Urbano	The leading organization split the project into five lots, each with unique forest and land use types.	75 km	€77 million euros(~ $80 million USD)	12 years	This project is multipart, aimed at achieving climate and community goals. It is a forest belt that will surround the city.	Soil restoration, ecosystem restoration, reduce CO2 emissions	Not provided

Urban Forestry

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
2 Billion Trees Program Canada	Canada	Government of Canada	Canadian citizens and organizations will be able to receive government funding to do tree planting projects throughout the country. There will be resources to address knowledge gaps in tree planting and maintenance processes	Throughout Canada, the total tree area is not known at this point.	$3.2 billion	10 years	This project aims to bring more trees to all parts of Canada, including rural, remote, and urban areas, on private and public lands.	Cool cities, increase biodiversity, clean air and water, reduce disaster risk	The project will not fund projects to plant trees in important ecosystems like grasslands, nor will they fund private projects that are “business as usual.”

Bolding indicates DOI affiliates.

Green Roofs

Name and Link	Location	Leading Organizations	Techniques Used	Size, ft^2	Cost	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
NOAA Satellite Operations Center	Suitland, MD	US General Services Administration, National Oceanic and Atmospheric Administration	Green roof	146,000	$81 million	Not provided	This project aimed to create a low-impact building for the satellite operations center.	Stormwater management	Not provided
Chicago City Hall Green Roof	Chicago	US Environmental Protection Agency, City of Chicago	Semi-intensive on a 1.5% slope, irrigation system along with rainwater collection	20,300	$2.5 million	1.5 years	This project was meant as a test to see how well a green roof would operate in Chicago, and it was a success in mitigating urban heat and propagating urban ecology (Dvorak).	Combat urban heat, improve air quality	It is crucial to secure funding for proper maintenance (Dvorak).
Hassalo on Eighth Green Roof	Portland, OR	American Assets Trust	Intensive and extensive on a 1% slope, wastewater treatment using a natural Organic Recycling Machine	38,000	The total price was not provided, but the project was refunded $1.48 million because of innovative stormwater management.	~1 year	This project was a part of multiple green roofs being used for wastewater treatment using the natural organic recycling machine. This project was a cutting-edge stormwater treatment strategy.	Reduce stormwater runoff, relieve stormwater treatment facilities	Because of the welcoming design, this project also achieved community engagement and use.

Bolding indicates DOI affiliates.

Pollinator Gardens

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Living Roof at 50 UN Plaza	San Francisco, CA	US General Services Administration	The green roof uses 8 in. of growing media to support succulents and native California plant species that provide nectar.	14,000 ft^2	Not provided	Not provided	Combination green roof with a succulent carpet and wildflower mix.	No	No
Smithsonian Urban Garden	Washington, DC	Smithsonian Institute	Installation of plants known to attract and support butterflies	11,000 ft^2	Not provided	Not provided	Butterfly habitat garden supports plants that have specific relationships to life cycles of eastern US butterfly species.	No	No
Jennings County Pollinator Habitat Program	Jennings County, IN	Jennings County Soil and Water Conservation District	Public education to spread word about pollinator declines, working with farmers to create pollinator habitat near farmland, and funded pollinator habitat creation on public and private property within the county	More than 600 habitat patches, ranging from 1 m^2 to >1 acre in size	Not provided	4.5 years	A county-wide pollinator habitat initiative	No	No

Bolding indicates DOI affiliates.

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Built Environments
17. Urban Stormwater and Runoff Management

DEFINITION

Urban areas have large areas of impervious surfaces, which cause water to run off during storms (rather than retaining water or allowing it to infiltrate into the ground). This creates issues with stormwater flooding and, in cities with combined sewer systems, can also lead to sewer overflows following rainfall. Nature-based solutions (NBS) strategies for urban stormwater and runoff management such as rain gardens, stormwater parks, permeable pavement, and bioswales are intended to reduce these issues by promoting water retention, infiltration, and evapotranspiration instead of runoff (Palermo et al. 2023).

TECHNICAL APPROACH

Technical specifics vary for different types of urban stormwater NBS, but the general approach is similar and can be summarized in the following steps:

1. **Identify the most critical stormwater issues within the area of interest and select appropriate locations and techniques to address them (FEMA 2021):** The Minnesota Stormwater Manual includes additional broadly relevant guidance on selecting NBS stormwater techniques (Minnesota Pollution Control Agency 2023a).
2. **Design the system components:**
   - **Rain gardens, bioswales, tree trenches, and stormwater parks:** This includes the dimensions and depth of the basin or ditch, structure and location of inflows and outflows, soil or other media, and vegetation selection (Scott et al. 2013). Stormwater parks often include built wetlands; see the built wetlands summary for more information on the design of those components.
   - **Permeable pavement:** This includes whether an underdrain is needed (depending on soil infiltration rates), slope and overflow structures to prevent flooding in severe storms, and pavement type (based on anticipated traffic load and environmental factors such as freezing temperatures; options include permeable pavers, pervious concrete, and porous asphalt) (Minnesota Pollution Control Agency 2022).
   - **Rainwater harvesting:** This includes the size of the storage tank (based on roof size and local precipitation rates) and its location, a gutter system to direct water from the roof into the storage tank, and a treatment system to achieve standards required for the intended use of the harvested water (Hunt 2021).

Table 17.1 NBS stormwater techniques and considerations

Technique	Description	Location Considerations
Rain garden	Vegetated depression that collects rainwater (from streets, driveways, roofs, etc.) and promotes infiltration (EPA 2023; Figure 1)	Must be able to direct runoff to rain garden location
Bioswale	Vegetated ditch similar to a rain garden but designed to capture larger volumes of runoff from impervious surfaces like parking lots and streets (Scott et al. 2013; Figure 2)	Often installed along streets/sidewalks
Tree trenches	Trench with trees planted in depressions to collect stormwater runoff for uptake by trees (Minnesota Pollution Control Agency 2023b)	Often installed along streets/sidewalks
Stormwater park	Recreational areas designed to flood during storms to reduce downstream peak flows; often include built wetlands (Puget Sound Regional Council 2022; Figure 3)	Requires larger area and inflow of stormwater (usually from conveyance infrastructure)
Permeable pavement	Alternative pavement materials that allow water to infiltrate rather than running off (Minnesota Pollution Control Agency 2022; Figure 4)	Easiest to install during new construction or renovation that requires replacing existing pavement
Rainwater harvesting	System to collect rainwater from roofs in a storage tank for later use (for irrigation, ponds/fountains, toilet flushing, etc.) (FEMP n.d.)	Site should have one or more uses for the collected water

Figure 17.1 Rain garden at Arlington National Cemetery

Photo courtesy Arlington National Cemetery

Figure 17.2 Bioswale at Arlington National Cemetery

Photo courtesy Arlington National Cemetery

Figure 17.3 Stormwater park in Milwaukee, WI

Photo courtesy Aaron Volkening

Figure 17.4 Permeable pavement in a Mississippi high school parking lot

Note: There is also a tree trench in the background.
Photo courtesy Mississippi Watershed Management Organization

3. **Install the system according to the design:**
   - **Rain gardens, bioswales, and tree trenches:** The general process is to (1) install temporary erosion and sediment controls and divert water from the site until the project is complete; (2) excavate the site to the appropriate depth and dimensions, including inlet and outlet locations and elevations; (3) install underdrain if required; (4) add soil or other media to fill the excavated area to the desired elevation; (5) plant vegetation and add surface cover (e.g., mulch, stone, grass); and (6) remove erosion and sediment controls and allow water flow into the project site (Scott et al. 2013).
   - **Permeable pavement:** The general process is to (1) install temporary erosion and sediment controls; (2) excavate the site, till, and grade the soil; (3) install underdrain (sloping toward outlet) if needed; (4) spread 4 to 6 in. of base stone; and (5) install paving material according to manufacturer specifications (Minnesota Pollution Control Agency 2022). Care is needed to not to over-compact porous asphalt or pervious concrete to avoid reducing infiltration capacity.
   - **Rainwater harvesting:** The general process is to (1) install the storage tank (tanks can be installed underground or aboveground), (2) install a filtration and treatment system, and (3) direct rainwater into the tank by modifying the existing gutter system or adding new gutters (Hunt 2021).

4. **Monitor vegetated systems:** It is important to regularly monitor the site as the vegetation becomes established and water plants (if conditions require), remove and replace dead plants, remove sediment accumulation, and repair erosion issues (Scott et al. 2013). Once vegetation cover is adequate, these tasks will need to be performed less regularly (see operations and maintenance section).

OPERATIONS AND MAINTENANCE

Rain gardens, bioswales, tree trenches, stormwater parks: Inspect at least twice during the growing season. Based on inspection, common maintenance includes mowing grass cover (if present), removing debris and sediment from inlets, weeding and removing invasive plants, and addressing any erosion issues (Scott et al. 2013).

Permeable pavement: Avoid surface clogging by vacuuming at least twice annually (more frequently if there is high sediment deposition), maintaining surrounding landscaping to reduce soil erosion onto the pavement, and minimizing use of sand for winter traction (Minnesota Pollution Control Agency 2022).

Rainwater harvesting: Clear debris and clean filter as needed, remove sediment from tank annually, ensure mechanical components (pump, treatment system, etc.) are functioning properly (FEMP n.d.). If water is used for drinking (rare), regular water testing is required.

FACTORS INFLUENCING SITE SUITABILITY

Rain Gardens, Bioswales, Tree Trenches, Stormwater Parks

- ✓ **Low tree cover:** Communities with limited canopy cover can use these strategies with planted trees to enhance tree cover as well as address stormwater issues.
- ✓ **Older communities with extensive existing development:** Tree trenches, bioswales, and rain gardens have relatively small footprints and are easier to add to existing developed areas.
- ✓ **Public view or access:** These strategies are aesthetically pleasing and larger sites, particularly stormwater parks, can provide recreational opportunities if there is public access.
- ✗ **Steep slope:** Rain gardens need to be installed in areas with low slopes so the bottom of the garden is flat.

Permeable Pavement

- ✓ **Highly urbanized areas:** Permeable pavement reduces the need for separate water retention facilities in urban areas where space is at a premium (Minnesota Pollution Control Agency 2022).
- ✓ **Low traffic:** Areas with pedestrian access or low-volume, low-speed roads and parking lots are suitable for permeable pavement (Minnesota Pollution Control Agency 2022).

- ✗ **Shallow water table:** Shallow depth to groundwater prevents permeable pavement from draining completely. Vertical separation of at least 1 ft is recommended for permeable pavement with an impermeable liner at the bottom, and at least 3 ft for permeable pavement without a liner (Minnesota Pollution Control Agency 2022).
- ✗ **High pollutant loading:** Areas that receive high volumes of debris, sediment, chemicals, or fuels are not good candidates for permeable pavement because of the potential for clogging or water contamination (Minnesota Pollution Control Agency 2022).

Rainwater Harvesting

- ✓ **Adequate rainfall:** The site should receive enough precipitation to supply water for its intended use (FEMP n.d.).
- ✓ **Large, shallow roofs:** These capture more rainfall than smaller or steeper roofs (FEMP, n.d.).

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?
Bioretention Illustrated: A Visual Guide for Constructing, Inspecting, Maintaining and Verifying the Bioretention Practice	Guidebook	2013	Chesapeake Stormwater Network	Written for the Chesapeake Bay Watershed but much of the information is broadly relevant	Introduction to principles of bioretention systems (rain gardens, bioswales) and overview of design and construction. Focuses on visual indicators to assess performance and maintenance needs. Also includes visual indicators for other urban stormwater management practices, including permeable pavement and filter strips.	✓	—	✓	—
EPA System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN)	Software	2014	US Environmental Protection Agency (EPA)	National	Decision support tool to select optimal stormwater practices. No longer being updated by EPA, but still in use.	✓	✓	—	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Minnesota Stormwater Manual	Website	2023 (continually updated)	Minnesota Pollution Control Agency	Written for Minnesota but much of the information is broadly relevant	Details on stormwater control practices, including many NBS. Includes design and construction guidelines, operations and maintenance information, assessing project performance, and case studies.	✓	✓	✓	✓
Planning Stormwater Parks	Guidebook	2022	Puget Sound Regional Council	Written for Puget Sound but much of the information is broadly relevant	Guidance for stormwater park planning and design, including information on engaging with communities, working with consultants, and post-construction operations	✓	✓	✓	✓
Rainwater Harvesting Tool	Online tool	Not provided	Federal Energy Management Program	National	Spatial information on the potential for rainfall harvest (in general and for irrigation) based on annual precipitation patterns	—	✓	—	—
Rain Gardens for RainScapes Technical Design Manual	Guidebook	2015	Department of Environmental Protection RainScapes Program, Montgomery County, MD	Written for Maryland but generally applicable for rain garden design (suitable plant species will vary by region)	Guide to designing and constructing a rain garden, including maintenance and trouble-shooting	✓	✓	—	—

GRAY INFRASTRUCTURE ALTERNATIVES

Urban stormwater and runoff management can be an alternative to gray stormwater infrastructure. The ability of an NBS urban stormwater project to replace or supplement gray infrastructure 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 NBS stormwater approaches. See the gray infrastructure alternative tables in the cross-cutting material for a comparison of NBS to gray stormwater infrastructure.

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Reduced flooding:** These NBS techniques are designed to address localized urban flooding by promoting water retention and infiltration, thereby reducing peak discharge (Copeland 2016). However, there is high variability in stormwater retention performance between and within techniques; more data is needed to improve the certainty of this outcome (Kõiv-Vainik et al. 2022).
- **Heat mitigation (all except rainwater harvesting and permeable pavement):** All vegetated urban stormwater techniques can help to reduce urban heat island effects through shading and evapotranspiration (Laurenz 2019, Sagrelius et al. 2022).
- **Carbon storage and sequestration (all except rainwater harvesting and permeable pavement):** All vegetated urban stormwater techniques promote carbon storage and sequestration by plants and trees (Copeland 2016).
- **Drought mitigation:** When sized and used properly, rainwater harvesting allows for on-site reuse of water, reducing pressure on the water supply system during droughts (Jones and Hunt 2010). Other urban stormwater NBS techniques promote infiltration that can help to recharge groundwater supplies during droughts (Li et al. 2009; Weerasundara et al. 2016).

Social and Economic

- **Recreational opportunities (stormwater parks only):** Stormwater parks can provide a variety of recreational opportunities, depending on their design, including hiking or walking trails, playgrounds, athletic fields and courts, picnic areas, and community gardens (Puget Sound Regional Council 2022).
- **Reduced erosion:** Slowing runoff flow reduces channel erosion (Li et al. 2009; Vijayaraghavan et al. 2021).
- **Increased property values (all except rainwater harvesting and permeable pavement):** Studies have found increases in residential property values when trees and other vegetation are present, and when properties have views of or access to recreational sites such as stormwater parks (Foster et al. 2011; Lee and Li 2009).

- **Aesthetics (all except rainwater harvesting and permeable pavement):** Rain gardens, bioswales, and stormwater parks are more aesthetically pleasing than gray stormwater infrastructure and can improve the aesthetics of streets, sidewalks, and parking lots (Foster et al. 2011; Weerasundara et al. 2016).
- **Aquifer recharge (all except rainwater harvesting):** Promoting infiltration recharges underlying aquifers (Li et al. 2009; Weerasundara et al. 2016).
- **Reduced energy use (rainwater harvesting only):** Harvesting and reusing water on-site reduces energy used to treat and transport water from local utilities (Copeland 2016).

Ecological

- **Improved water quality (all except rainwater harvesting):** Slowing runoff and promoting infiltration traps sediment and other nutrients, improving the quality of water reaching streams and other water bodies (DeBusk and Wynn 2011; Vijayaraghavan et al. 2021).
- **Reduced runoff:** All of the urban stormwater and runoff management techniques collect, retain, or promote infiltration of precipitation (Li et al. 2009; Weerasundara et al. 2016).
- **Supports wildlife (all except rainwater harvesting and permeable pavement):** Rain gardens, bioswales, and stormwater parks create habitat for native wildlife species (Weerasundara et al. 2016).
- **Supports native plants (all except rainwater harvesting and permeable pavement):** It is recommended to plant rain gardens, bioswales, and stormwater parks with native plants adapted to local conditions (Weerasundara et al. 2016).

BARRIERS AND SOLUTIONS FOR PRACTITIONERS

Several barriers are common across many of the NBS strategies; these are described in more detail in Section 1 of the Roadmap. Additional notes about the barriers specific to urban stormwater and runoff management are included here.

- **Expense**
- **Capacity**
- **Public opinion**
- **Conflict with other land uses**
- **Regulation:** Especially local ordinances, building codes, plumbing and health regulations, street width and parking requirements, and restrictions on using reclaimed water (Copeland 2016).
- **Lack of effectiveness data:** In particular, gaps in data on performance in different climates and function over time (Copeland 2016; Weerasundara et al. 2016; Vijayaraghavan et al. 2021).

Economic

- **Financing:** It can be difficult to acquire financing for these types of projects, which can have longer payback times than similar gray infrastructure approaches (Copeland 2016).

Community

- **Displacement:** NBS urban stormwater projects can contribute to gentrification via increased housing costs, resulting in displacement of lower-income community members and exacerbating inequality (Taguchi et al. 2020; Walker 2021). Planning for community protection alongside stormwater projects—for example, by supporting cooperative housing, rent control, or participatory budgeting—can help avoid these unintended consequences (Walker 2021).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Robbins Stormwater Park and Midlothian Creek Restoration Project	Chicago, IL	Metropolitan Water Reclamation District of Greater Chicago	Diversion channel to stormwater pond, streambank stabilization, stormwater park with naturalized wetland area, rain garden, bioswales	52 acres	20 million	Planned for two years (in progress)	Stormwater park and other project components are designed to reduce overbank flooding from Midlothian Creek and protect property and infrastructure in Robbins, IL.	Flooding	No (project is in progress)
Arlington Stormwater Wetland Park	Arlington, WA	City of Arlington	Stormwater park, including constructed wetlands	21 acres	1.325 million	Not available	Stormwater park with trails, picnic area, dog park, and wildlife viewing as well as a constructed wetland for stormwater, reclaimed water, and clean effluent from water treatment plant	Flooding	Helpful to have staff from multiple city departments involved (stormwater, natural resources, planning, parks). Early public outreach leads to greater acceptance. Maintenance is a good opportunity for students and community volunteers.

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Plum and Walnut St. Green Intersection	Lancaster, PA	City of Lancaster	Tree trenches, curb extension planter for rain garden, permeable pavement, rainwater harvesting	Not available	115,000 (estimated)	Not available	Green stormwater component were added as part of a roadway realignment project to improve traffic safety, enhance pedestrian amenities, and reduce stormwater runoff	Flooding	High road salt levels required transition to Mid-Atlantic coastal grasses
Silver Lake Beach Parking Lot	Wilmington, MA	Town of Wilmington	Permeable pavement, rain gardens, bioswales	Approximately 25,000 ft^2 of permeable pavement	448,000 (includes design, construction, and three years of maintenance	Approximately 8 months	Stormwater management at a popular parking area for recreational use of Silver Lake was designed to reduce stormwater runoff to the lake to improve water quality	No	No adverse effect on groundwater underneath permeable pavement. Fewer closures of swimming beach due to bacterial contamination following project.

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Built Environments
18. Wildlife Road Crossing Structures

DEFINITION

Wildlife road crossing structures (WRCSs) are infrastructure built with the joint goals of increasing habitat connectivity across roads and reducing wildlife–vehicle collisions. These structures can take many forms and are sited and designed differently depending on the type of wildlife present in the nearby ecosystem (FHWA 2011). Different forms of WRCSs fall along a continuum of gray to green infrastructure; all include some form of gray infrastructure, but most also use natural infrastructure (FHWA 2011). Roads are direct threats to wildlife because of the potential for wildlife–vehicle collisions that cause individual mortalities, but also because roads fragment wildlife habitat and can limit natural wildlife movement patterns throughout a landscape (Bissonette and Cramer, 2008). Wildlife–vehicle collisions can result in both personal injury and property damage (Huijser et al. 2007). WRCSs are therefore installed to protect human life and property and maintain healthy wildlife populations.

TECHNICAL APPROACH

When designing a road, the first step to minimize wildlife disruption is to try and avoid impacting certain sensitive or essential habitats or connectivity corridors. When avoidance is not possible, WRCSs are the next-best option to reduce impacts to wildlife and risks of wildlife–vehicle collisions. There are three primary steps to installing a WRCS, summarized below from the Federal Highway Administration's Wildlife Crossing Structure Handbook (FHWA 2011).

1. **Habitat connectivity planning**: The first step to creating successful WRCS is to do a landscape-level assessment to understand what habitats the road is impacting, which wildlife species use those habitats, and which species are most likely to be impacted by the road. Habitat connectivity planning can either be done at the project level (specific to a particular road project) or, preferably, at the system level (taking into account the broader regional road network). System-level planning allows for an assessment accounting for how the regional road network impacts wildlife movements. Connectivity planning may include a regional landscape assessment of wildlife connectivity needs within a transportation corridor. If possible, predicted climate-induced range shifts of wildlife species should be incorporated into the connectivity plan to ensure that WRCSs are designed with likely future scenarios in mind. Connectivity planning often involves wildlife movement modeling, collection of field data on wildlife locations and movements, and/or roadkill data. The connectivity planning stage will help make decisions about how many WRCSs to install and where to site them. For more information on connectivity planning and the types of data needed for these types of assessments, see Chapter 3 of the Wildlife Crossing Structure Handbook. For an example of a connectivity plan at a state level, see an example plan created for North Carolina (Sutherland et al. 2022).

2. **Selection of appropriate WRCS design type(s):** There are two primary types of WRCS: *overpasses* and *underpasses* (Figures 1–2). There are multiple subtypes of both over- and underpasses, and selecting which types to use and how to space them depends on the goals of the WRCS, the type of wildlife expected to use them, and the landscape topography. Some of the most common WRCS forms can be found in Table 18.1. For more information on how to select a WRCS design, see Chapter 4 of the Wildlife Crossing Structure Handbook.
3. **Installation of WRCS**: The final step is installation of the selected WRCS type(s). It is possible that, in addition to the WRCS, there will also be installation of wildlife-behavior–modifying structures to encourage use of the WRCS and/or discourage crossings in areas where WRCS do not exist. These behavior-modifying structures include installation of fencing, planting or removal of vegetation with high nutritional value in particular locations, intercept feeding (placement of food sources), and aversion techniques including use of lights, lasers, water sprays, or mirrors (Huijser et al. 2007). It is typically most efficient and effective to install WRCS during road construction; however, it is also possible to retrofit existing roads to allow for wildlife crossings (USFS and NPS, 2017).

Figure 18.1 Wildlife underpass in San Diego County, CA

Photo courtesy USFWS Pacific Southwest Region

Figure 18.2 Wildlife overpass in Arizona

Photo courtesy USFWS Pacific Southwest Region

OPERATIONS AND MAINTENANCE

Maintenance of each WRCS listed in Table 1 will differ. Maintenance details for each structure type can be found in the entries of Appendix C of the Wildlife Crossing Structure Handbook. Example maintenance activities include irrigating vegetation on the crossing structures during the first few years of operation, repairing damage to gray infrastructure components, and removing obstructions to underpass structures.

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Existing wildlife corridor:** WRCS should be placed in locations where wildlife would naturally travel (e.g., in riparian areas, along ridgelines) and in locations important for landscape connectivity (FHWA 2011).
- ✗ **Steep slope:** Areas with steep slopes are not well-suited to WRCS (FHWA 2011).

Table 18.1 Common types of WRCSs

Overpass Designs	Underpass Designs
Landscape bridge: Designed exclusively for wildlife use. Because of their large size, they are used by the greatest diversity of wildlife and can be adapted for amphibian and reptile passage	***Viaduct or flyover:*** The largest of underpass structures for wildlife use, but usually not built exclusively for wildlife movement. The large span and vertical clearance of viaducts allow for use by a wide range of wildlife. Structures can be adapted for amphibians and reptiles, semiaquatic, and semiarboreal species.
Wildlife overpass: Smaller than landscape bridges, these overpass structures are designed to meet the needs of a wide range of wildlife from small to large.	***Large mammal underpass:*** Not as large as most viaducts, but the largest of underpass structures designed specifically for wildlife use. Designed for large mammals, but small- and medium-sized mammals readily use them as well.
Multiuse overpass: Generally the smallest of the wildlife overpasses. Designed for mixed wildlife and human use. This wildlife crossing type is best adapted in human-disturbed environments and will benefit generalist species adapted to regular amounts of human activity and disturbance.	***Multiuse underpass:*** Design similar to large mammal underpass; however, management objective is co-use between wildlife and humans. Design is generally smaller than a large mammal underpass because of the type of wildlife using the structures, along with human use. These structures may not be adequate for all wildlife, but usually result in use by generalist species common in human-dominated environments (e.g., urban or periurban habitats). Large structures may be constructed to accommodate the need for more physical space for humans and habitat generalist species
Canopy crossing: Designed exclusively for semiarboreal and arboreal species that commonly use canopy cover for travel. Meets the needs of species not built for terrestrial travel that generally have difficulties crossing open, nonforested areas	***Underpass with waterflow:*** An underpass structure designed to accommodate the needs of moving water and wildlife. These underpass structures are frequently used by some large mammal species, but their use depends largely on how they are adapted for animals' specific crossing needs. Small- and medium-sized mammals generally use these structures, particularly if riparian habitat or cover is retained within the underpass
	Small- and medium-sized mammal underpass: One of the smaller wildlife crossing structures. Primarily designed for small- and medium-sized mammals, but species use will depend largely on how the crossing may be adapted for their specific crossing needs
	Modified culvert: Crossing that is adaptively designed for use by small- and medium-sized wildlife associated with riparian habitats or irrigation canals. Adapted dry platforms or walkways can vary in design and are typically constructed on the lateral interior walls of the culvert and above the high-water mark.
	Amphibian and reptile tunnels: Crossing designed specifically for passage by amphibians and reptiles, though other small- and medium-sized vertebrates may use as well. Many different amphibian and reptile designs have been used to meet the specific requirements of each species or taxonomic group

Adapted from the Wildlife Crossing Structure Handbook

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?
Wildlife Crossing Structure Handbook: Design and Evaluation in North America	Guidebook	2011	US Department of Transportation, Federal Highway Administration	North America	This guide provides details on placement and selection of appropriate types of WRCS	✓	✓	✓	—
US DOT Wildlife Crossing Structures Portal	Website	n.d.	US Department of Transportation	National	This portal contains links to WRCS resources specific to particular regions of the United States, including assessments of structure effectiveness	✓	✓	—	—
Wildlife and Roads: Decision Guide and Project Database	Tool and database	n.d.	Utah State University, USGS, National Academies Transportation Research Board	National	This website contains a decision guide that helps users plan and implement WRCS projects. It also contains a database of WRCS projects in the US.	✓	✓	✓	✓
Evaluation of the Use and Effectiveness of Wildlife Crossings	Report	2008	National Academies Transportation Research Board	National	This report contains a literature review that explores the development of a tool that guides the selection, configuration, and location of WRCS	—	✓	—	—
Wildlife Vehicle Collision and Crossing Mitigation Measures	Guidebook	2007	US Department of Transportation, Federal Highway Administration; Montana Department of Transportation	Written for Montana, but most information is broadly applicable	This report reviews 39 mitigation measures that help reduce wildlife–vehicle collisions and provide habitat connectivity for wildlife crossings. The guide is focused on structures for large terrestrial mammals.	✓	✓	✓	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Measures to Reduce Road Impacts on Amphibians and Reptiles in California	Guidebook	2021	California Department of Transportation, University of Montana, Herpetofauna Consultants International	Written for California but most information is more broadly applicable	This best management practices guide describes practices for retaining or improving habitat connectivity for amphibians and reptiles in California	✓	✓	✓	—
Highway Crossing Structures for Wildlife: Opportunities for Improving Driver and Animal Safety	Report	2021	US Forest Service	National	This report reviews a vision for designing a road network that incorporate WRCS for human and wildlife benefits. It includes a description of common challenges faced when installing these structures	—	✓	—	✓

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Social and Economic

- **Public health and safety:** It has been estimated that wildlife–vehicle collisions with deer alone result in more than 200 human fatalities, 29,000 human injuries, and more than $1 billion in property damage each year in the United States (Conover et al. 1995). WRCS help reduce the likelihood of collisions that can cause human injury or mortality.

Ecological

- **Supports wildlife:** Road infrastructure is a direct threat to wildlife both because of the potential for wildlife–vehicle collisions that cause individual mortalities, but also because roads fragment wildlife habitat and can limit natural wildlife movement patterns throughout a landscape. In some cases, highways are a movement barrier that can reduce survival probability of a particular wildlife population as a result of habitat restrictions and/or limited gene flow (Bissonette and Cramer 2008; Huijser et al. 2007; Ament et al. 2021). WRCSs are intended to support wildlife by reducing these negative effects of roads and highways. Additionally, as wildlife range shifts occur as a result of climate change, WRCSs can help animals to shift their ranges accordingly (Ament et al. 2021).

- **Increased habitat connectivity:** WRCSs help sustain wildlife populations and ecosystem integrity by connecting habitats at a local scale (Ament et al. 2021).

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 wildlife road crossing structures are included here.

- **Expense**
- **Capacity:** Large-scale transportation plans often do not include considerations for WRCSs, and additional efforts must be made to ensure wildlife mitigation measures are included in road planning and design. Additionally, resource constraints often make it difficult to sufficiently coordinate and plan to install WRCSs (Ament et al. 2021).
- **Public opinion**
- **Conflict with other land uses**
- **Regulation**
- **Lack of effectiveness data**

Community

- **Administrative constraints:** Roads often cross jurisdictional boundaries and coordination across agencies, governments, and landowners is often required to install WRCSs (Ament et al. 2021).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Idaho State Highway 21 Underpass	Idaho	Idaho Transportation Department, Idaho Department of Fish and Game	Underpass and associated fencing	Not provided	Not provided	Not provided	A location along Idaho State Highway 21 near Lucky Peak Reservoir was identified as an important wildlife migration corridor for deer and elk. The underpass was built to reduce wildlife-vehicle collisions.	No	No
Banff Wildlife Overpasses	Trans-Canada Highway, Canada	Parks Canada	WRCS including six wildlife overpasses with native plants and associated fencing and 38 wildlife underpasses	Not provided	Not provided	Not provided	Overpasses were part of a large effort in the 1980s to reduce wildlife–vehicle collisions	No	Have reduced wildlife–vehicle collisions by 80%
Colorado State Highway 9	Grand County, Colorado	Colorado Department of Transportation	A series of wildlife crossings plus wildlife funnel fencing along 10 mi of State Highway 9. It included two overpasses, five underpasses, and 10 mi of fence	Along 10 mi of highway	~$10million	Not provided.	Implemented to reduce wildlife–vehicle collisions with mule deer and elk	No	The project is considered a success, and is projected to pay for itself in 22 years as a result of reduced collision costs

Bolding indicates DOI affiliates.

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Inland Wetland Habitats
19. Nontidal Wetland Restoration

DEFINITION

Nontidal wetland restoration is the rehabilitation of a degraded wetland so that its hydrology, vegetation, and ecological processes approximate, to the extent possible, the original natural condition prior to modification (USDA 2021). Nontidal wetlands include any wetlands that are not inundated by tidal waters; this summary applies to nontidal wetlands generally but includes some details specific to arid wetlands and ephemeral wetlands. There are also separate summaries for the related strategies of peatland restoration, stream restoration, floodplain reconnection, and built wetlands.

Specific activities to restore wetlands depend on the wetland type and how it has been modified. Frequently, wetland modification occurs via drainage by surface ditching or tile drains (Biebighauser 2023, Schilling 2022). These wetlands can be restored by removing those alterations—for example, by filling or blocking ditches. Strategies to restore arid wetlands include installing rock detention structures, earthen berms, log dams, soil remediation, and riparian restoration (Wilson and Norman 2018). Invasive species removal and replanting with native species are also common wetland restoration techniques.

TECHNICAL APPROACH

1. **Site preparation:** Site preparation is often needed to remove debris and invasive species from the restoration site and may also require microtopographic alterations to ensure the wetland is slightly lower than the surrounding landscape so it will hold water (Calhoun et al. 2017; Ferren et al. 1998; USDA 2023). This is particularly important for wetlands that were previously filled to create a flat surface for agriculture, forestry, or other uses.

2. **Hydrologic restoration:** Nontidal wetland restoration frequently requires hydrologic restoration to return inundation extent and frequency to a natural state. Hydrologic restoration techniques depend on the type of drainage present in the degraded wetland:

   - **Ditch filling:** For wetlands with surface ditching, hydrology can be restored by filling in the entire ditch and regrading to the natural topography. A simpler but less effective method is to use a ditch plug, which dams the ditch at its lowest point, but does not fully restore the hydrology (Gibson et al. 2020, Sargent and Carter 1999).

   - **Removing tile drains:** For wetlands with tile drains, hydrology can be restored by removing all tile drains and filling in the resulting channel. Another option is to use tile breaks, which leaves the tile drains in place, but plugs the flow through the drains in multiple places. This technique is simpler and commonly used, but does not completely restore hydrology (Gibson et al. 2020, Sargent and Carter 1999).

- **Detention structures:** For wetlands in arid regions that need assistance with water retention following intense precipitation, rock detention structures or log dams can be used to slow down water, protect soil, and reduce erosion (TRC 2023; University of Arizona 2023; EPA 2021; Norman et al. 2022; Silverman et al. 2019).
- **Levee removal:** Wetlands that have been cut off from a nearby stream or river by a levee will benefit from levee removal (Pess et al. 2005). See the floodplain reconnection summary for more information on this technique.

3. **Revegetation:** After hydrologic restoration is complete, the area can be left to revegetate naturally, or can be planted with appropriate species. When selecting a vegetation strategy, it is important to consider the possibility of invasive species colonization, especially under natural revegetation. Planting can be done using plugs (most feasible for small areas) or by seed dispersal (more successful in large areas or frequently submerged areas) (Rodrigo 2021).

OPERATIONS AND MAINTENANCE

Invasive species, duckweed, and algae should be removed from the restored wetland annually, and trash and debris cleared as needed. Repairs to rock detention structures or log dams may be required periodically. If present, ditch plugs should be mowed and repaired about once a month. After major storms, logs and branches will need to be cleared from spillways. If problems with muskrat, woodchuck, or other animal burrows are observed, holes may need to be filled.

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Existing wetlands:** Restoration within a complex of existing wetlands will have the greatest chance of success (USDA 2021). In arid regions, connection to a larger system of intermittent streams can help channel water to wetlands during rainfall, which replenishes water in the wetland and reduces erosion.
- ✓ **Low-lying agricultural areas that are frequently flooded**: Frequently flooded agricultural areas are a sign that a former wetland was drained and planted with crops. These restoration scenarios typically involve creating tile breaks and ditch plugs to restore the hydrology (Sargent and Carter 1999).
- ✓ **Degraded area with hydric soils still present:** Hydric soils are an indicator that a wetland once existed on the site. Often covered with construction fill or trash, hydric soils can form the basis of a functioning wetland once the debris has been removed (Biebighauser 2023).
- ✓ **Landscape has many depressions containing clay soil:** Clay soil is more impervious, allowing for greater water retention within the wetland. Clay soil combined with a slight depression provides a natural bowl that can hold water (Biebighauser 2023).
- ✓ **Soils containing high levels of sulfidic material:** An indicator of a potential wetland site is when sulfur has been reduced to hydrogen sulfide. This is the source of

the common "rotten eggs" smell associated with wetlands. While not all restoration sites must meet this condition to be successful, the "rotten eggs" smell is a sign of wetlands bacteria at work (Beall n.d.).

- **Near a brownfield or landfill site:** Many species that inhabit wetlands are highly sensitive to toxic chemicals. Wetland restoration results in the soil being inundated, meaning that there is the potential for chemicals in the soil to pollute the water.
- **Slopes in the area are greater than 3°:** Wetlands need to be located in a flat basin for water to pool. Even gentle slopes can cause water runoff to leave the wetland (Uuemaa et al. 2018).
- **Near existing infrastructure (roads, off-road vehicle trails, built structures, etc.):** Wetlands are sensitive to disturbances from foot traffic, and ephemeral wetlands are especially so. During dry seasons, hikers may wander off nearby trails and into the dry wetland, endangering fauna in the mud. Off-road vehicle use and roads create obstacles for amphibians attempting to migrate between vernal pools (Uuemaa et al. 2018).
- **Area that experiences heavy grazing:** Heavy grazing pressure can significantly degrade wetlands as grazers eat many of the wetland plants. Waste products from the grazing animals can also cause nutrient pollution in the wetland.
- **Has a salinity content greater than 0.5 ppt:** Nontidal wetlands are freshwater ecosystems that cannot tolerate salt water (Cowardin et al. 1979).

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?
USDA Part 650 Engineering Field Handbook, Chapter 13: Wetland Restoration, Enhancement, or Creation	Book chapter	2021	US Department of Agriculture – Natural Resources Conservation Service	National	Guide to the planning, design, implementation, and monitoring of wetland restoration and enhancement. Also includes methods for assessing wetland function based on hydrogeomorphic principles.	✓	✓	✓	—
A User's Guide to Wetland Restoration, Creation and Enhancement	Guidebook	2003	Interagency Working Group on Wetland Restoration (National Oceanic and Atmospheric Administration, Environmental Protection Agency, Army Corps of Engineers [USACE], Fish and Wildlife Service, and Natural Resources Conservation Service)	National	Developed by the Interagency Workgroup on Wetland Restoration, this guidebook provides information on restoration project planning, implementation, and monitoring.	✓	✓	✓	—
The Wetlands Restoration Guidebook	Guidebook	Not provided	Maryland Department of the Environment	Written for Maryland but information is generally applicable	High-level reference aimed at a general audience interested in wetland restoration. Useful information on site characteristics that increase or reduce suitability for wetland restoration.	—	✓	—	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Minnesota Wetland Restoration Guide	Guidebook	2012	Minnesota Board of Water and Soil Resources	Written for Minnesota, but information is applicable to wetland restoration in the entire upper Midwest	Ecological and engineering principles for restoring wetlands, including site assessment, design and construction, vegetation establishment, and monitoring and ongoing management.	✓	✓	✓	—
Wetland Assessment, Restoration and Management	Training	Offered periodically	US Fish and Wildlife Service	National	In-person, 36-hour course focused on evaluating degraded wetlands for restoration potential and designing wetland restoration projects. Open to US Department of the Interior employees and contractors.	—	—	—	—
Riparian Restoration in the Arid and Semi-Arid Western US	Document	2003	USACE	Western United States	Produced by USACE, this resource details restoration methods for riparian and arid wetland habitat across the Western United States. Topics covered include plant species selection, planting techniques, and monitoring procedures.	✓	✓	✓	✓
Riparian Habitat Restoration for the Arid Southwest	Training	2023	Wetland Training Institute	Southwest United States	Held in San Diego, this two-day in-person training teaches participants the fundamentals of arid wetland restoration site selection, planning, and installation. The class takes field trips to successful restoration projects in the region in addition to identifying common mistakes.	✓	✓	—	✓

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Wetland restoration prioritizing, a tool to reduce negative effects of drought; An application of multicriteria-spatial decision support system (MC-SDSS)	Journal article	2018	Saeideh Maleki, Ali Reza Soffianian, Saeid Soltani Koupaei, Saeid Pourmanafi, and Sassan Saatchi	Global	The authors developed a model to determine which area of a wetland would provide the most ecosystem services if restored. Because water is the limiting factor in arid wetland restoration, this tool provides a framework to best allocate scarce water resources.	✓	✓	—	✓
Dryland Watershed Restoration With Rock Detention Structures: A Nature-Based Solution to Mitigate Drought, Erosion, Flooding, and Atmospheric Carbon	Journal article	2021	Jennifer Gooden and Richard Pritzlaff	Southwest United States	This resource explains how rock detention structures have been used to restore arid watersheds across the Southwest United States and the plethora of ecosystem services they provide. The authors also provide four case studies of successful restoration projects.	✓	—	—	✓
Soil Salinity and Sodicity in Drylands: A Review of Causes, Effects, Monitoring, and Restoration Measures	Journal article	2021	Ilan Savi, Niels Thevs, and Simone Priori	Global	As soil salinization is one of the greatest threats to arid wetlands, this resource guides practitioners through the restoration process of desalinating soils. Techniques covered include salt flushing and leaching, chemical remediation, organic and microbial remediation, and phytoremediation.	✓	✓	—	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Management and Conservation of Temporary Ponds (pg. 300–305)	Journal article	2009	International Conference on Mediterranean Temporary Ponds	Global	This resource focuses on controlling hydroperiods as the primary tool for ephemeral wetland management and restoration. The authors give insight on how to create artificial hydroperiods which rejuvenate ephemeral wetlands.	✓	—	—	—
A Guide for Creating Vernal Ponds	Guidebook	2002	USDA Forest Service	National	The author lays out in-depth information about the planning and construction of a vernal pond. The guide provides practical site suitability and budgeting advice to help get projects off the ground.	✓	✓	—	—

GRAY INFRASTRUCTURE ALTERNATIVES

Nontidal wetland restoration can be an alternative to several gray infrastructure approaches: stormwater drainage systems to address urban runoff and artificial aquifer recharge systems to add water to aquifers. The ability of a wetland 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 wetland restoration. See the gray infrastructure alternative tables in Section 1 for a comparison of wetland restoration to these alternatives.

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Drought mitigation:** Wetlands help capture excess runoff during intense precipitation events and slowly recharge groundwater aquifers via percolation. This allows for higher aquifer levels, reducing drought severity (Biebighauser 2002, Uhlman et al. 2020).

- **Reduced flooding:** Wetlands help reduce water runoff, preventing water from entering larger waterbodies and thus reducing flooding around those waterbodies (Biebighauser 2002). While large, permanent wetlands may have the most significant impact on the hydrological cycle, smaller, ephemeral wetlands have an outsized impact on flood mitigation because of their ability to store water temporarily. Restoring ephemeral wetlands in tandem with permanent wetlands maximizes the water storage capacity of the watershed (Zedler 2003).
- **Reduced wildfire risk:** In arid regions, wildfire severity is often determined by fuel load and soil moisture. Arid wetlands help retain water in the soil that can act as fire breaks and reduce fuel load by preventing trees from succumbing to drought, thus reducing wildfire severity. Furthermore, a functioning watershed reduces erosion and uprooted trees (which adds to the fuel load), making the region better prepared to manage future wildfires (Villarreal et al. 2022).
- **Heat mitigation:** Wetlands can cause significant reductions in air temperature, especially in urban or arid areas, helping mitigate heat. Because cooling ability becomes marginally smaller as the wetland increases in size, smaller ephemeral wetlands have a greater cooling potential than larger wetlands per acre (Wu et al. 2021).
- **Carbon storage and sequestration:** Nontidal wetlands, including arid and ephemeral wetlands, have been shown to store more carbon than estuaries (Nahlik and Fennessy 2016). This is known as *teal carbon*, and wetland restoration can help enhance carbon deposition into soil (Norman et al. 2022). However, it can take between three and 23 years after restoration for a wetland to turn into a net carbon sink (Valach et al. 2021).

Social and Economic

- **Recreational opportunities:** Restored wetlands provide venues for fishing, hunting, and wildlife watching.
- **Jobs:** Workers will need to be hired to restore wetlands, providing a boost to the local economy.
- **Mental health and well-being:** Wetland restoration enhances green space, which improves residents' mental health and well-being.
- **Cultural values:** Wetlands are not well-understood by the public. Restoring wetlands can help residents connect with this unique ecosystem, in addition to learning about the rare species that they contain. Wetlands are also places of significance in many Indigenous cultures.
- **Scientific research:** Skin secretions from amphibians are vital components of pharmaceutical research seeking to create new antiviral drugs (Hocking and Babbitt 2014). Ephemeral wetlands are vital habitats for endangered amphibians.
- **Aquifer recharge:** Wetlands are effective at recharging groundwater aquifers by facilitating an exchange between surface and groundwater in the hyporheic zone (Jolly et al. 2008). Wetland restoration means that more water will be available for agricultural, industrial, and domestic uses.

- **Reduced erosion:** Many arroyos and temporary streams in the arid United States have steep gradients, making them prone to significant erosion during heavy precipitation events. Arid wetlands help slow the flow of water and stabilize riparian areas. Furthermore, many arid wetland restoration projects involve installing erosion-control structures, which further strengthen watershed resilience against erosion (Wilson and Norman 2018).

Ecological

- **Improved water quality:** wetlands improve water quality by absorbing particulates and harmful pollutants, preventing them from running off into larger waterbodies (Calhoun et al. 2017; De Steven and Lowrance 2011).
- **Supports wildlife:** Wetland habitat supports threatened species populations, especially for reptiles, amphibians, and wetland-dependent birds, bats, and fish (De Steven and Lowrance 2011). In the United States, nine species of branchiopods, 20% of reptiles, and 40% of amphibians are threatened with extinction (IUCN 2023). These species rely on ephemeral wetlands as their primary habitat, meaning that conserving this habitat is vital to their survival (Deil 2020). Many migratory species, especially birds, use arid wetlands as an intermediate resting place during their journey (Jaensch and Young 2010).
- **Increased primary productivity:** Wetlands have unusually high levels of primary productivity, which helps enhance the species richness of the region (Simovich 1998).
- **Enhanced biodiversity:** Wetlands have a large number of endemic species and niche specialists, both of which are especially vulnerable to extinction. Wetlands also provide water sources to many other species, helping to support biodiversity.

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 nontidal wetland restoration are included here.

- **Expense**
- **Capacity**
- **Public opinion**
- **Conflict with other land uses:** Ephemeral wetlands are frequently cleared for agricultural use because of their small size, the relative ease of draining them, and their rich hydric soils that help improve yields (Schuyt 2005). In arid regions, urban development is often centered around ephemeral wetlands as the population needs a reliable source of water. Therefore, ephemeral wetlands are disproportionately targeted for development compared to other habitats (Smallbone et al. 2011). Cattle grazing in arid regions rely on arid wetlands as a vital source of water. Unfortunately, grazing pressures are not conducive to the health of arid wetlands, with cattle eating many

wetland plants and reducing the amount of water available to the ecosystem (Heffernan 2008). Potential sites for arid wetland restoration often overlap with future lithium mining operations. Geothermal brine and salt-rich playas are ideal spots for mining because of their lithium deposits but are also key for arid wetlands because of their water sources. With the United States striving to scale up its domestic lithium mining operations to support the electric vehicle industry, it is likely many of these sites will be developed into mines (DOE 2022).

- **Regulation:** For a waterbody to be protected under the Clean Water Act, it must be connected to downgradient navigable waters, according to the Supreme Court ruling *Sackett v. Environmental Protection Agency* (Puko and Barnes 2023). Unfortunately, many wetlands do not meet this threshold because they are isolated from other waterbodies and are nonnavigable, meaning that a landfill, construction site, or heavy industry could be sited nearby.
- **Lack of effectiveness data**

Community

- **Mosquitos:** Mosquitos are an integral part of the wetland ecosystem. Mosquito larvae help control algae blooms and eutrophication in the wetland and are vital parts of frog and salamander diets (PNHP n.d.). Some communities may oppose ephemeral wetland restoration because of this nuisance (PNHP n.d.). However, mosquitoes that harbor diseases harmful to humans, especially the *Culex* genus, prefer anthropogenic habitats over ephemeral wetlands, and natural predation generally obviates the need for mosquito control.
- **Arid wetland restoration:**
  - **Water allocation concerns:** The western United States, where the vast majority of arid wetlands are located, has always struggled with providing enough water for domestic, industrial, and agricultural uses. Because of this scarcity, little water is left for arid wetlands, which need to be replenished by runoff and snowpack because of high rates of evapotranspiration. While arid wetlands can help to mitigate the water shortage in the long run by recharging aquifers, many communities are unwilling to sacrifice water withdrawals upfront (Lemly et al. 1993).
  - **Urban development:** Arid wetlands are often targeted for urban development because they can provide a reliable source of water to sustain an urban population in arid regions. Unfortunately, urban development heavily degrades arid wetlands by changing the local hydrology and draining the wetland for development (Hollis 1990). Furthermore, arid wetlands are located in flood-prone areas, meaning that developments near them may suffer significant flood damage. This can be seen in Nogales, a city straddling the US–Mexico border, which has experienced numerous lethal floods (Freimund et al. 2022).

- **Ephemeral wetland restoration:**
    - **Off-road vehicle use:** Off-road vehicle users are often attracted to ephemeral wetlands because of their relatively open nature and muddy, yet navigable, soils. However, this activity causes extreme degradation to the wetland and its ecological community (Biebighauser 2002).

Ecological

- **Time to restore function:** Restored wetlands may take years to reach functional equivalency with natural, intact wetlands (Gutrich and Hitzhusen 2004).
- **Invasive species:** Even after being removed during the restoration process, many invasive aquatic plants recolonize wetlands. Their geographic mobility is due to their seed dispersal via migratory birds, which often stopover in wetlands (Reynolds et al. 2015). Therefore, continuing invasive species removal must occur as part of the normal maintenance processes.
- **Eutrophication and algal blooms:** Ephemeral and arid wetlands often suffer from eutrophication because they have little outflow, resulting in most of the excess nutrients staying within the wetland (Kido and Kneitel 2021). Overgrowth of algae and phytoplankton reduces dissolved oxygen levels and the wetland depth (Sánchez-Carrillo and Álvarez-Cobelas 2001, de la Cruz et al. 2017).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Dusky Marsh Restoration Project	Baskett Slough National Wildlife Refuge, OR	**US Fish and Wildlife Service (USFWS),** Oregon Department of Fish and Wildlife	Removing water control structures, dam removal, adding natural debris and ditch plugs	98	Not provided	8 weeks	To restore the hydrology of Dusky Marsh, workers removed dams and water control structures. They then built a ditch plug to keep water in the wetlands and added in natural debris.	No	All restoration activities had to be completed in an eight-week period before the wetland was inundated.
Watergate Wetlands Restoration Project	Delaware Gap Nationa Recreation Area, NJ and PA	**National Park Service (NPS)**	Dam, pond, and invasive species removal	20	Not provided	10 months	Contractors removed a dam and corresponding pond that had been filled with invasive species. They then reseeded plants native to ephemeral wetlands.	No	Biological monitors helped remove any animals from the area before the restoration work began.
Wetland Jewels Restoration Project	Carson and Santa Fe National Forests, NM	The Nature Conservancy, US Department of Agriculture Forest Service, Amigos Bravos and Western Environmental Law Center	Ditch plugs, microtopographic alterations	~1,000	Not provided	Ongoing	To restore these remote wetlands, workers are building ditch plugs, one-rock dams, and altering the topography.	Inland flooding, drought	A 10-day cap on grazing was implemented to help the wetlands recover during the restoration process.

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Del Sol Vernal Pool Enhancement Project	Santa Barbara, CA	University of California Santa Barbara, California Conservation Corps, State Coastal Conservancy, Isla Vista Recreation and Park District	Ditch plugs, microtopographic alteration, debris removal	12	13.2 million	1 year	Workers constructed ditch plugs to keep water from flowing out and removed soil and debris.	No	This project was part of a research study determining whether created wetlands were as biologically diverse as historic ones that were being restored.
North Dakota Prairie Pothole Restoration Project	Northwest North Dakota	**Bureau of Reclamation**	Tile breaks, removing agricultural fill	1,018	Not provided	1 year	Tile breaks were cut and agricultural fill was removed to return agricultural lands to their original state as ephemeral wetlands.	No	Studies showed that flora quickly repopulated the restoration sites after construction was finished, but not to the same extent as undisturbed wetlands.
Spring Peeper Meadow Restoration Project	Chaska, MN	University of Minnesota, Minnehaha Creek Watershed District	Tile breaks, invasive species removal	30	Not provided	3 years	Workers applied herbicides to remove invasive species, removed agricultural tile to restore the hydrology and then reseeded the wetland.	No	Invasive species declined as trees gradually shaded more of the wetland.

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Proctor Valley Vernal Pool Restoration Project	San Diego National Wildlife Refuge, CA	**USFWS,** City of San Diego, Chaparral Conservancy.	Invasive species removal, microtopographic alterations	38	$1.7 million	7 years	Team members removed invasive species, dug shallow depressions in the terrain, and replanted native plants.	Drought	Restricting off-road vehicle use in this area has been challenging.
Ciénega San Bernardino Wetland Restoration	San Bernardino National Wildlife Refuge, AZ	**USFWS, US Geological Survey (USGS)**	Gabion installation, invasive species removal, cattle grazing elimination	51	Not provided	12 years	Gradually, workers built 46 gabions and one check dam to help keep water in arid wetlands. The removal of invasive species and cattle grazing also helped the wetland recover.	Inland flooding	The watershed continues into Mexico, where partners also performed wetland restoration to expand the functioning portion of the ecosystem.
Chiricahua Mountains Watershed Restoration Project	Chiricahua National Monument, AZ	**USGS, NPS,** private landowners	Check dam, gabion, and leaky weir installation	~300	Not provided	20 years	More than 20,000 rock detention structures were installed, including small check dams, leaky weirs, and gabions.	Inland flooding, drought	This watershed has 28% more flow than nearby watersheds that haven't been restored.

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Babocomari Watershed Project	Southeast Arizona	**USGS,** The Walton Family Foundation	Gabion and leaky weir installation	20	Not provided	2 years	Gabions and leaky weirs were installed as a part of a managed aquifer recharge project to help retain water after large rainfalls.	Drought	The gabions resulted in downstream scouring. This limited water ponding above the gabion to help sustain a wetland. Installing additional gabions upstream helped mitigate this problem.
Glorieta Creek Wetland Restoration Project	Pecos National Historic Park, NM	**NPS**	Levee removal and native plant installation	7	98,9996	2 years	Workers removed a levee that was blocking water flow in between Glorieta Creek and the arid wetland. The site was regraded, and native plants were installed.	Inland flooding	A portion of the levee was left in place until the site was established and was then later removed.
Resaca Wetland Restoration Project	Palo Alto Battlefield National Historic Park, TX	**NPS,** University of Arizona	Levee and ditch removal, native plant installation	34	Not provided	2 years	To convert this agricultural field back to its natural state, workers removed levees and ditches and planted more than 50,000 plugs of gulf cordgrass.	No	Because the wetland was an important battle site in the Mexican-American War, managers had to take into account historic as well as ecological considerations.

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Arroyo Seco Restoration Project	Pasadena, CA	City of Pasadena, USACE	Invasive species removal, stream reconfiguration	34	2.56 million	2 years	Much of the Arroyo Seco and surrounding wetlands had been degraded by impacts of urban development. Workers reconfigured the stream to avoid developed areas and removed invasive species.	Inland flooding	Restoring water quality has been challenged because the areas directly upstream and downstream of the restoration site are heavily modified.
Cienega Creek Restoration Project	Las Cienegas National Conservation Area, AZ	**Bureau of Land Management (BLM),** Cienega Watershed Partnership	Invasive species removal, erosion remediation, native plant installation	339	Not provided	4 years	To mitigate erosion, volunteers removed invasive species, restored soils, and installed native plants.	Drought	The stakeholder engagement was critical, because the project spans private and BLM lands.
Blue Hole Cienega Restoration Project	Santa Rosa, NM	**USFWS,** New Mexico Department of Game and Fish	Rock dams, grazing management, and prescribed burns	116	Not provided	3 years	Rocks were installed and cattle grazing was limited to protect this arid wetland fed by alkaline spring water. Prescribed burns are occasionally used to remove invasive species and promote the growth of native species.	Drought	There has been significant debate about whether cattle grazing should be allowed at this site. While cattle remove invasive species, they also damage wetland soil.

Bolding indicates DOI affiliates.

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Inland Wetland Habitats
20. Peatland Restoration

DEFINITION

Peatlands are a type of inland wetland where waterlogged soils prevent plant material from fully decomposing. There are two types of peatlands: *tropical peatlands*, characterized by high precipitation and temperature, and *northern peatlands,* which are interspersed among boreal forests and coastal areas (IPS n.d.b.). The United States is home only to northern peatlands, which are primarily found in Alaska, the Great Lakes region, New England, and the Atlantic Coastal Plain (MN DNR 2023, Minasny et al. 2019). Sphagnum moss is the building block of peatlands, with layers of moss growing over water and providing a foundation on which other plants can grow (Andreozzi n.d.). Peatlands, which include bogs, fens, and peat swamps, are vital carbon sinks, with twice as much carbon stored in peatlands as in all the world's terrestrial forests. Peatlands are on the decline, with 35% of peatlands lost globally since 1970 (Kopansky 2019). To reverse this trend, peatland restoration and conservation projects aim to rehabilitate peatlands to their natural state as carbon sinks. Most peatland restoration projects involve altering the hydrology of the site to rewet the peat. Techniques often used include installing peat dams, plastic piling and bundling, water control structures, and transferring sphagnum moss into the site (IPS n.d.a)

TECHNICAL APPROACH

Peatland restoration is tailored toward sites that have experienced peat mining or have been drained for agriculture. Individual restoration techniques should be selected based on the site-specific factors. However, most peatland restoration projects first remove drivers of peatland degradation, then restore peatland hydrology, and finally reintroduce plants.

1. **Removing drivers of peatland degradation:**
   - **Invasive species removal:** Altered hydrology and eutrophication can create conditions that favor invasive species. Invasive species increase the risk of fire, outcompete native species and impede the peat forming process. Common invasive species in peatlands include glossy buckhorn (*Frangula alnus*), reed canary grass (*Phalaris arundinacea),* and the common reed (*Phragmites australis*) (Cohen et al. 2020).
   - **Pollution control:** Peatlands are negatively impacted by airborne soot pollutants from nearby industrial facilities and poor water quality from nutrient pollution. The unique soil structure of peatlands is negatively impacted by high nitrogen and phosphorus concentrations, leading to the release of carbon in the soil (Li et al. 2022). Limiting the amount of airborne and waterborne pollution that enters a peatland is necessary before introducing more water to the area as a part of hydrological restoration (Monteverde et al. 2022). This involves siting projects away from heavy industry and working with landowners upstream to install riparian buffers.

- **Grazing control:** While limited grazing can benefit peatlands by removing invasive species and excess fuel, intense grazing pressures can degrade peatlands. Grazing reduces the amount of carbon stored in peatlands and alters the plant community composition (Ward et al. 2007). Limiting grazing gives peatlands the opportunity to naturally regenerate.
- **Fire control:** Fire management in peatlands is a highly controversial issue, with many organizations arguing that prescribed burns should be eliminated from peatlands (IUCN UK PP 2023). Prescribed burns on peatlands should be low intensity, located away from bare peat, in flat areas, and performed during wet conditions. Prescribed burns are meant to remove excess vegetation that could cause larger catastrophic peatland fires in the future (Ashby and Heinemeyer 2021). Other fire control measures such as forest thinning and invasive species removal should be considered before a prescribed burn is conducted.
- **Forest to bog restoration:** Once peatlands are dried out, the sphagnum moss is often replaced by trees that are better adapted to the new hydrological system. Tree harvesting clears the way for peat to be reintroduced, with dead trees left on-site and mulched to keep the biomass within the ecosystem. Furrow blocking and ground smoothing are then performed to restore the flat topography of the peatland. This technique is often combined with plastic piling or peat dams (descriptions follow) to keep water in the peatland (NatureScot 2020).

2. **Restoring peatland hydrology:** For drained peatlands, restoration involves blocking drainage outlets to keep water in the peatland (Figure 1). This promotes the waterlogged conditions that make peatlands such effective carbon sinks (IPS n.d.a).
    - **Peat dams:** Plugging the mouths of ditches and channels with peat can help keep water in the peatland. *Peat dams*, which are walls of peat blocking water drainage out of the peatland, are common rewetting tools. Working under dry conditions, damming the most upstream part of the system first and spacing dams closer together as slopes get steeper is vital to project success (Joosten and Duene 2021).
    - **Plastic piling and bundling:** In areas where it is not feasible to create a peat dam, plastic piling and bundling can help block drainage points. Large sheets of plastic are sunk into the drainage ditch and the surrounding peat, preventing any leakages. The sheets are often reinforced with timber to ensure stability (Mainprize 2021).
    - **Wood piling dams:** Alternatively, wood piling dams can be used to regulate runoff. A dam built with planks inserted deep into the soil is placed perpendicular to the ditch. During construction, the ditch should be drained using temporary dams or bypass channels to promote stability (Joosten and Duene 2021).
    - **Metal dams:** In areas that experience significant water pressure and frequent inundation, metal dams can be used to alter hydrology. Panels of sheet metal can be used to replace wood or plastic piling in dams. While metal is more durable, it can also be more expensive (Joosten and Duene 2021).

Figure 20.1 Water control structure to block a drainage outlet in Great Dismal Swamp, VA

Photo courtesy US Fish and Wildlife Service Northeast Region

- **Stone dams:** In areas where buoyant materials such as peat or wood are not suitable, stone dams can be used to keep water in the peatland. Stones can be used to reinforce peat dams or plastic piling. Stone *gabions*, metal cages filled with stone, can be placed in the middle of culverts. The gabions will get clogged with peat, which will then block water from flowing out of the peatland (Joosten and Duene 2021).
- **Bunding interventions:** Bunding aims to keep water on the peat restoration site by constructing a retaining wall around the perimeter. The wall can be made of a variety of materials, but commonly consists of peat. Deep bunding is done to prevent water from leaking out of cracks in the peat. To slow down water flow, surface bunding is installed in areas of wide, but shallow, water flow (NatureScot 2020).
- **Backfilling:** *Backfilling*, also known as *infilling*, involves filling up entire drainage ditches with substrate. While the substrate does not have to be peat moss, it should be nutrient-poor and impermeable. Further compacting the material increases impermeability. To prevent erosion, the surface should be covered with vegetation (Joosten and Duene 2021).

3. **Reintroducing plants:**
   - **Moss layer transfer technique (MLTT):** *MLTT* is the process of transferring moss from a donor site to the restoration site. Ensuring that donor sites have a similar species makeup to the restoration site is critical for success. Furthermore, certain species have been identified as *recalcitrant*, meaning they fail to become established once transplanted. Recalcitrant species vary by region; researching and avoiding the use of these plants in MLTT will help promote peatland growth (Hugron et al. 2020). To protect the newly transferred sphagnum moss, it is recommended that the restoration site is covered by a thin layer of straw to increase water availability and regulate temperature conditions.
   - **Seeding:** If the desired post-restoration ecosystem is a peat swamp with trees, then seed dispersal may be necessary. Selected seeds should be from pioneer species that have adapted to the conditions of primary succession. Once these plants have become established, then the seeds of more shade-tolerant plants should be planted in a second phase (Joosten and Duene 2021). If plant growth is struggling, phosphorus fertilizer can also be applied. This aids the growth of vascular plants that will stabilize the moss as it gets established (Rochefort et al. 2003).
4. **Post-restoration clean-up:** Once the restoration activities have been completed, it is important to repair damage caused by temporary access roads that serviced the restoration site. Heavy machinery is needed to conduct peatland restoration and access to the site is often a challenge. Soil in peatlands is unstable and muddy, meaning that damage will be done moving equipment to the site. Restoring track sites after the project is done is important to ensure that the temporary access roads are not turned into permanent passageways for unauthorized users (NatureScot 2020).

OPERATIONS AND MAINTENANCE

Operations and maintenance will typically center around continued removal of invasive plants (if needed) and ensuring that water control structures are operating properly to maintain proper hydrological conditions within the peatland site.

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Locations where peat has been previously mined:** Sites that have experienced peat mining still have the elements of functioning hydrological processes. Mined sites just need donor peat material to replace the peat that has been extracted (MN DNR 2012).
- ✓ **Ample water supply:** Water is the driving force behind a successful peatland ecosystem. If there is not enough water in the area or the site does not naturally hold water, then peatland restoration should be reconsidered (Quinty and Rochefort 2003).
- ✓ **At least 50 cm of peat remaining:** Sites with at least 50 cm of remaining peat still have bog conditions, meaning that they can support a functioning peatland. However, thinner layers of thoroughly decomposed peat are an exception to this rule, as this often also indicates bog conditions (Quinty and Rochefort 2003).

- ✓ **Water pH of 5.1 or lower:** While some fens can have higher pH than this, acidic conditions are often what distinguishes peatlands from other inland wetland habitats. For areas with more basic pHs, wetland restoration is recommended instead (Quinty and Rochefort 2003).
- ✓ **Flat topography:** Peatlands need poor drainage and low levels of runoff to remain waterlogged. Flat topography slows water flow and allows water to stay in the peatland.
- ✗ **Limited site access:** Because of their hydrologic conditions, peatlands are often inaccessible for significant portions of the year. Attempting to haul heavy equipment to a remote restoration site may cause more harm than good to the ecosystem (Artz et al. 2019).
- ✗ **Mineral-rich soils:** Peatlands are nutrient- and mineral-poor ecosystems. Peatland soils have high carbon content instead of minerals. Therefore, mineral-rich soils will not support a peatland (SEPA 2019).
- ✗ **Near sources of nutrient pollution:** Nutrient pollution significantly hinders the ability of a peatland to function. Unless the source of the nutrient pollution is being mitigated, then peatland restoration should not occur near discharges of nutrient pollutants (Schumann and Joosten 2008).
- ✗ **Near waste disposal sites:** Rewetting peatlands as part of a restoration project has the potential to expose water to toxic waste buried in the soil. This is problematic because the mixing of water and toxic waste could contaminate the drinking water supply (Schumann and Joosten 2008).
- ✗ **Completely inundated site:** While peatlands thrive in waterlogged conditions, sites that are frequently completely inundated are more suitable for aquatic habitats than peatlands. Rapid inundation of a peatland may cause carbon to be released. Slow rewetting is a better strategy to maintain the peatland as a carbon sink (Zak and McInnes 2022).

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?
Global Peatland Restoration Manual	Guidebook	2008	Greifswald University	Global	This guide categorizes peatland restoration activities by their benefits. The authors also include information about monitoring, site suitability, and stakeholder involvement.	✓	✓	✓	—
Practical Peatland Restoration	Technical report	2021	Office of the Secretariat of the Ramsar Convention	Global	Focused on techniques for peatland restoration, this document outlines designs for blocks and bunds as well as methods for revegetation. Reducing leakage and tree removal are also covered.	✓	—	—	—
Guidelines for Wetland Restoration of Peat Cutting Areas	Guidebook	2004	Bridge Project	Designed for Europe but most of the information is more broadly applicable	This guide is tailored to restoration projects following commercial peat extraction. The authors cover restoration strategies based on the starting condition of the peatland, setting goals for the restored peatland, and the environmental impacts of rewetting peatlands.	✓	✓	—	✓
Minnesota Wetland Restoration Guide	Guidebook	2019	Minnesota Department of Natural Resources	Designed for the Great Lakes region but most of the information is more broadly applicable	Allowing managers to dive deeply into every aspect of the restoration process, this guide sequentially leads readers from planning to monitoring. The engineering design section is especially helpful for manipulating peatland hydrology. An additional guidance document is also available.	✓	✓	✓	—
Peatland ACTION – Technical Compendium	Guidebook	2022	NatureScot	Designed for Scotland but most of the information is more broadly applicable	This guide covers a variety of restoring techniques, including artificial drains, bunding, peat stabilization and forest to bog restoration. Also included are helpful links to additional resources.	✓	—	—	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Petland Restoration Guide: Second Edition	Guidebook	2003	Canadian Sphagnum Peat Moss Association and New Brunswick Department of Natural Resources and Energy.	Designed for Canada but most of the information is more broadly applicable	Encompassing both peatland ecology and restoration strategies, this guide provides troubleshooting advice for common problems that projects often encounter. Additional topics covered include monitoring, alternative management strategies, and descriptions of common North American peatland species.	✓	✓	✓	—
Conserving Bogs: The Management Handbook	Guidebook	2019	International Union for Conservation of Nature National Committee for the United Kingdom Peatland Programme	Designed for the United Kingdom but most of the information is more broadly applicable	This guide focuses on conserving peatlands, highlighting management strategies such as limiting grazing, fires, access, and erosion. The authors also provide a framework for creating peatland-specific management strategies.	✓	✓	✓	—
Best Practice Book for Peatland Restoration and Climate Change Mitigation	Guidebook	2021	LIFE Peat Restore Project	Europe	Outlining the principles of peat rewetting, this guidebook recommends the best practices for a successful project. Additional topics covered include monitoring, creating floating islands and reintroducing sphagnum moss.	✓	—	✓	✓
An Overview of Peatland Restoration in North America: Where Are We After 25 Years?	Journal article	2017	Rodney A. Chimner, David J. Cooper, Frederic C. Wurster, and Line Rochefort	North America	The authors overview trends of peatland restoration in North America, highlighting spatial and strategic shifts. Specific techniques for unique ecoregions across the continent are also discussed, as well as case study projects.	✓	—	—	✓

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Reduced wildfire risk:** Wet peat is less flammable than dry peat. Even in a large area of dry peat, small patches of wet peat can stop the spread of smoldering flames. Thus, rewetting peat via restoration activities can significantly reduce wildfire risk (Prat-Guitart et al. 2016). This is especially important because peat fires can burn underground for many months and release copious quantities of carbon during combustion.

- **Carbon storage and sequestration:** Peatlands are the world's largest terrestrial carbon store, storing more carbon than all other vegetation types despite only covering 3% of global land surface (IUCN 2021). While functioning peatlands are powerful carbon sinks, degraded peatlands can become carbon sources. Peatland restoration can avoid enormous amounts of carbon emissions from the large net difference in carbon fluxes between degraded and functioning peatlands. Net carbon emissions reductions could reach 24.5 metric tons CO_2/ha/year of peatland restored, making restoration an efficient way to combat climate change (Richardson et al. 2022).

- **Heat mitigation:** Peatland vegetation can have a cooling effect on the surrounding environment. Wet peat decreases evaporation rates during dry and hot periods, keeping water in the environment. However, once a peatland is dried out, it displays higher rates of evaporation. Therefore, peat rewetting is key to lowering surface temperatures around peatlands (Weiss and Vlček 2023).

- **Drought mitigation:** During droughts, peatlands can regulate water loss. As conditions get drier, the peat increases surface tension, which maintains the moisture content in the peat. Wet peatlands are better able to weather droughts, with surplus water allowing them to shut down evaporation and retain water (Kettridge and Waddington 2014).

- **Reduced flooding:** During heavy rainfalls, local tributaries are often overwhelmed with excess water. Peatlands can help attenuate floodwaters by retaining water during flood peaks. Peatlands often serve as a piece in the larger floodplain (see summary) puzzle, working with nearby wetlands and forests to absorb water (Tanneberger et al. 2021). In addition, land subsidence, which increases flood vulnerability, often occurs when peatlands are developed into agricultural or mining sites. When the peatland is drained, the moisture that gives peat soils its unique characteristics is taken away, causing the soil to compress (Bonn et al. 2016). Restoring peatlands reduces elevation loss and flood risk.

Social and Economic

- **Jobs:** Contractors will need to be hired to perform the restoration activities, stimulating the local economy.

- **Recreational opportunities:** Restored peatlands are ideal sites for a variety of recreational activities including hunting, birdwatching, and hiking.

- **Cultural values:** Peatlands are often misunderstood by the public. Peatland restoration and conservation provides an opportunity for greater awareness and appreciation of the vital ecosystem services peatlands provide.
- **Mental health and well-being:** Peatlands enhance greenspace, boosting mental health and psychological well-being.
- **Reduced erosion:** Erosion in peatlands is particularly problematic because it results in more carbon emissions. Peatland restoration projects can help remediate erosion by revegetating eroded sites, altering the topography to soften slopes, and fertilizing bare spots of peat to induce growth (Milner et al. 2021).

Ecological

- **Enhanced biodiversity:** The Ramsar Convention identified peatlands as the most important type of wetlands for the conservation of biodiversity. The diversity of peatland ecosystems means that means a greater variety of species are present. Peatlands support biodiversity in other habitats as well, providing refuges to species displaced from nearby developed areas, supporting breeding birds, providing rest stops for migrating birds, and buffering watersheds. Restoring peatland vegetation can help protect peatland biodiversity (Minayeva et al. 2016).
- **Improved water quality:** Drained peatlands can leach nutrients such as ammonia, contributing to nutrient pollution further downstream. By preventing peatlands from being drained or rewetting peatlands, these excess nutrient discharges can be mitigated (Holden et al. 2006). Peatlands also effectively absorb excess nutrients and suspended sediments from nearby waterbodies (Limpens et al. 2006; Nieminen et al. 2015).
- **Reduced runoff:** Peatlands can control runoff by absorbing excess water into the soil. When runoff filters through peatlands, peatlands increase the amount of dissolved organic carbon in the water. This helps enhance the water chemistry in surrounding waterbodies (Tunaley et al. 2017).

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 peatland restoration are included here.

- **Expense**
- **Capacity**
- **Public opinion:** Peatlands are often misunderstood as barren and desolate ecosystems, contributing to a lack of awareness about the biodiversity, carbon sequestration and water quality benefits they provide. Educating residents about the benefits of peatland restoration will enhance community buy-in for the project (Moxey et al. 2021).

- **Conflict with other land uses:** The most significant threat to northern peatlands is conversion to arable land. Conversion involves draining the peatland, which aerates the soil and increases respiration, resulting in an increase of carbon emissions (Qiu et al. 2021). Peatlands are often targeted for cultivation because of their flat topography and proximity to water sources. While peatland restoration is not expensive compared to restoring other ecosystems (ranging between \$1200–\$3000 per acre), it does not directly generate revenue like agriculture does (MN BWSR 2012). Peat mining is still common in the United States because of its diverse uses in turf maintenance, agriculture, and sewage treatment. While most peat consumed in the United States is imported from Canada, large amounts are still mined in Florida, Michigan, Minnesota, and Maine (USGS 2023). Mined peatlands seldom recover without restoration (Rochefort et al. 2003).
- **Regulation:** In the past, many peatland restoration projects have been initiated in response to Clean Water Act (CWA) requirements. The CWA requires that peatland restoration must occur after peat extraction or to offset the degradation of a peatland elsewhere (Chimner et al. 2017). However, the Supreme Court decision *Sackett v. Environmental Protection Agency* significantly narrowed the scope of the CWA, excluding many wetlands that are not connected to a larger riverine system (Puko and Barnes 2023). Some peatlands may no longer be protected, curtailing this driver of restoration.
- **Lack of effectiveness data**

Community

- **Vehicle trails:** Informal vehicles trails across peatland are becoming increasingly common as off-road vehicle usage increases. While many off-road vehicles enter a peatland merely for recreational purposes, others use peatlands as entry points for construction or mining projects. Vehicle trails, which are often reinforced by plastic mesh or wooden planks, disturb the hydrology of the peatland and deposit chemical contaminants (Williams-Mounsey et al. 2021). Vehicular access to a restoration site needs to be limited.

Ecological

- **Variable greenhouse gas emissions fluxes:** While peatland restoration can store vast amounts of carbon in the long term, it generally takes around 20 years for a peatland to return to a carbon sink after restoration. Projects often encounter a trade-off between sphagnum growth and methane (CH_4) emissions. A higher water table allows for the sphagnum to grow faster, but risks higher CH_4 emissions. A lower water suppresses CH_4 emissions but also inhibits Sphagnum growth. This trade-off varies spatially, often depending on the plant community involved (Nugent et al. 2018).

- **Impact on donor sites:** To extract peat from a donor site, the peatland must first be dewatered. Then, heavy machinery removes the desired peat layers. This process results in significant damage to the donor site, fragmenting the peat layers and disturbing hydrological processes (Nwaishi et al. 2015). However, these impacts can be limited by using a high ratio of peat surface collected to peat surface restored (between 1:10 and 1:15). This also aids plant establishment at the restoration site (Rochefort et al. 2003).
- **Limited storage of peat:** Because of logistical constraints, extraction of peat from the donor site often cannot occur at the site same time as restoration. Thus, peat blocks are often stored until the restoration team is ready to plant them. However, during storage, peat blocks can dry out, causing the peat to shrink and develop large pores. This reduces the water storage capacity of the peat and increases the likelihood of peatland flooding. Limiting storage time is critical to a successful restoration project (Lehan et al. 2022).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Pocosin Lakes Pocosin Lakes National Wildlife Refuge Restoration Project	Pocosin Lakes National Wildlife Refuge, NC	**US Fish and Wildlife Service (USFWS)**	Peat dams and dikes, wood dams (flashboard risers), ditch plugging	30,000	1.5 million	20	Farmers had previously drained the peatlands for agriculture. The team used a variety of dams and dikes to block drainage canals and rewet the peatlands.	Wildfire, drought	After the project was completed, the frequency and severity of wildfires significantly decreased.
Sax-Zim Bog Restoration Project	Northern Minnesota	The Nature Conservancy, US Department of Agriculture Forest Service, Minnesota Department of Natural Resources, Ecosystem Investment Partners	Backfilling ditches	23,220	Not provided	Not provided	This peatland was previously ditched for timber production. Contractors are now working to restore the peatland hydrology by backfilling the ditches.	Wildfire	The project is financed through carbon markets. Amphibious excavators are being used to navigate the difficult terrain.
San Joaquín River Delta Restoration Project	Central California	Sacramento-to-San Joaquín Delta Conservancy	Converting farmland to peatland via levee alteration	3,500	24 million	Ongoing (4 years expected)	To reverse pervasive land subsidence in this region, farmland is being reconverted into peatland. Altering levees will allow for the peatland to be reincorporated into the larger floodplain mosaic.	Flooding	The managed water table, warm weather, and long periods of plant growth have resulted in large amounts of methane emissions. This means it will take longer for the peatland to return to a carbon sink.

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Big Meadows Restoration Project	Rocky Mountain National Park, CO	**National Park Service,** Colorado State University	Blocking ditch entrance with galvanized sheet metal	156	Not provided	1	Completely backfilling the ditch was deemed impractical as the nearest road was more than 2 mi away. Instead, galvanized sheet metal was placed over the outflow point of the ditch.	Drought	The hydrological regime is highly dependent on snowmelt. This results in the fen occasionally drying out in summers with little precipitation post-restoration.
Seney Peatlands Restoration Project	Seney National Wildlife Refuge, MI	**USFWS**	Ditch plugging, plastic piling, and installation of water control structures	3,460	Not provided	2 years	Nine earthen ditch plugs were installed to block the Walsh Ditch, which had drained the peatland. Plastic piling was also used to reinforce the ditch plugs.	Wildfire	In spring, when extra water needs to be discharged from the peatland, water control structures were installed to divert the water back into the natural watershed.
Great Dismal Swamp Restoration Project	Dismal Swamp State Park, NC	**USFWS,** US Army Corps of Engineers, North Carolina Department of Natural and Cultural Resources, North Carolina State University	Water control structures with flashboard risers	1,927	Not provided	1	Drainage ditches and canals were dug to drain peatlands. Water control structures were installed to help the peatland retain water. In addition to stopping water from entering the canals, the project also reduced loss of groundwater.	Wildfire	Water control structures allowed for the project to control the peatland hydrology while only blocking the canal in select places.

Bolding indicates DOI affiliates.

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Riverine Habitats
21. Beaver Management and Beaver Dam Analogs

DEFINITION

Beavers are large, semiaquatic, herbivorous rodents that reside in the Northern Hemisphere. Only one species of beaver, the North American beaver (*Castor canadensis*), lives in the United States, covering most of the contiguous states (except for Florida, small patches of the Midwest, and the arid Southwest) and southern Alaska (USFS n.d.). Beavers are prominent ecosystem engineers because of their dam-building prowess. Beaver dams alter the hydrology of streams and small rivers, generating a multitude of benefits including filtering pollution, creating wetlands, storing groundwater, preventing floods, and sequestering carbon (Goldfarb 2018). In the pre-Columbian era, there were an estimated 250 million beavers in North America, a number that declined to 100,000 in the early 1900s as a result of intensive trapping (Ortiz and Dello Russo 2021; Goldfarb 2018). Since then, trapping regulations and beaver reintroductions have resulted in an estimated 10 to 15 million beavers living in North America today (Ortiz and Dello Russo 2021; Bardeen 2022). Beaver management refers to a strategy of increasing beaver populations through beaver reintroductions, enhancing beaver habitat, and promoting human–beaver coexistence (Jordan and Fairfax 2022). If an area wants to reap the benefits of beaver dams but does not have any beavers, beaver dam analogs (BDAs) can be built. BDAs are human built structures meant to mimic the design and function of beaver dams (Anabranch Solutions n.d.).

TECHNICAL APPROACH

Beaver Management

Beavers are intelligent animals and can reproduce quickly, which has allowed them to rapidly recolonize much of their former range (Schulte and Müller-Schwarzei 1999). To fully take advantage of the work of these impressive ecosystem engineers, managers can use the following strategies:

- **Beaver reintroductions:** In areas with historic beaver populations but no present-day colonies, a beaver reintroduction program can help improve local riverine processes. *Beaver reintroductions*, also known as *beaver translocations*, are human-facilitated beaver colonizations of a new territory. Before a beaver reintroduction can occur, livestock grazing must be managed to allow enough biomass to grow to provide food for beavers. Planting trees and riparian vegetation to support the beavers may also be necessary (Baker and Hill 2003). Beavers are then usually trapped, quarantined, tagged, and released.

  To avoid disrupting thriving beaver populations, translocation projects often target beaver colonies in urban areas that are generating nuisance complaints and are at risk of being euthanized if not moved. When trapping beavers, a variety of traps can be used, including box traps, suitcase-style traps, and nonlethal cable restraints (Doden et al. 2022). Regulations require beavers to be quarantined in a holding facility for a short period of time to reduce the transmission of disease. During this time beavers should be fed tree cuttings and root vegetables (Campbell-Palmer and Rosell 2015). Beavers can also be fitted with tracking collars to enhance monitoring if desired. Then, beavers should be released at the desired restoration site. While beavers may initially disperse to establish their own territory, over time, their movement will mirror normal beaver activity (Doden et al. 2022).

- **Enhancing beaver habitat:** If human-mediated beaver reintroduction is not feasible, then enhancing beaver habitat can entice beavers to naturally colonize the area. Reducing competition from other herbivores such as cows, elk, and deer will help promote beavers. This can be done by fencing off beaver habitat, killing the other herbivores via population control programs, or reintroducing natural predators such as wolves. Another option is to increase beaver food sources. Beavers like to eat willow and cottonwood trees, which can be planted along rivers. A final option is to reduce beaver predation rates. Humans are by far the main cause of beaver mortality, so more stringent trapping regulations can be implemented to support beaver populations (Pollock et al. 2023).
- **Promoting human–beaver coexistence:** Studies have shown as beaver densities increase, the willingness of residents to take lethal action against beavers increases as well (Siemer et al. 2013). Sources of human–beaver conflict include beavers cutting down commercially valuable timber, flooding properties, and blocking culverts. To reduce tree cutting, installing wire mesh cages around the base of the tree as well as dousing the tree with paint mixed with sand can be effective. For flooding concerns, installing flexible pond levelers or Clemson beaver pond levelers can lower water levels behind a beaver dam. Culvert-protective fencing or replacing a too-small culvert with a properly sized one (also benefitting riverine connectivity) are effective at mitigating conflicts with beavers (Pollock et al. 2023). Furthermore, nonlethal beaver control is much cheaper, saving an average of $229 per site per year (Callahan et al. 2019).

Beaver Dam Analogs

BDAs are meant to mimic natural beaver dams in arid or urban areas where beavers struggle to survive (Figure 1).

Like beaver dams, BDAs are engineered to eventually fail after a couple years (Anabranch Solutions n.d.). Additionally, the quantity of BDAs is more important than the quality, as a complex of BDAs can exert a larger influence on a river than one individual dam (Shahverdian et al. 2019). BDAs often attract beavers to colonize the area, where they will maintain and live in human-built dams. Constructing BDAs involves the following steps:

1. **Build up fill material:** A rudimentary wall of fill material should be placed along the river, with the height of the wall not exceeding 1 ft above the water's surface. Fill material can be sourced from the surrounding area and can include logs, stones, mud, and turf (Shahverdian et al. 2019).
2. **Build additional layers:** Next, additional layers of fill material must be added to reinforce the structure. Each successive layer should add around an additional foot of height to the dam until the structure has reached the desired crest elevation (Shahverdian et al. 2019).

Figure 21.1 Beaver dam analog at the North Slope Ochoco Holistic Restoration Project, OR

Photo courtesy NRCS Oregon

3. **Install posts:** Cuttings of midsized trees taken from the surrounding area should then be added to the structure. Posts should be driven into the ground vertically behind the fill material. The top of the post should be approximately 1 ft higher than the crest of the fill material. The number of posts installed is dependent on the level of structural stability desired (Wheaton et al. 2019).
4. **Construct willow mattress:** Weave willow branches into the downstream side of the dam. This will reduce water energy if the dam is overtopped (Shahverdian et al. 2019).
5. **Reinforce dam:** Plug up any leaks in the dam with small pieces of organic material (Shahverdian et al. 2019).

OPERATIONS AND MAINTENANCE

Maintenance activities may include subsequent beaver reintroductions, education and awareness campaigns about the benefits of beavers to help prevent local pushback and/or lethal action against beavers, or repair and maintenance of BDAs as they break down over time.

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Low gradients:** Stream power is reduced at lower gradients, making it easier for beavers to construct and maintain dams. This also allows beavers to flood a larger area with a smaller dam (Ritter et al. 2020).
- ✓ **Narrow channels:** Narrow channels allow beavers to build more stable dams that can better withstand high seasonal flows (Ritter et al. 2020).
- ✓ **High channel complexity:** Complex channels allow for a greater density of feeding areas as well as providing smaller channels of water that are easier to dam. A complex river morphology also dissipates floodwaters that could compromise the structural integrity of the dam (Scrafford et al. 2018).
- ✓ **High canopy cover of woody riparian vegetation:** Woody vegetation provides beavers with an ample source of both food and building materials for dams. Woody vegetation close to the water also helps beavers avoid predators since they do not have to travel as far to forage (Ritter et al. 2020).
- ✓ **Low-lying areas directly adjacent to the stream:** Low-lying riparian areas allow beavers easy access to foraging space. Additionally, low-lying riparian zones allow beavers to flood a larger area with a smaller dam, resulting in an outsized impact on the riverine system (Ritter et al. 2020).
- ✗ **Heavily incised channels:** Beavers need to access the floodplain to harvest vegetation, and channel incision limits this access (Scamardo and Wohl 2019).
- ✗ **Large rivers:** Beavers typically only live in first- or second-order streams that can be feasibly dammed. Larger rivers have too-deep water and are too wide to support beavers (Scamardo and Wohl 2019).

- **Frequent, intense flooding:** Streams that are especially flood-prone will deter beavers as their dams will be destroyed. If a two-year flood is powerful enough to destroy a beaver dam, then restoration should not occur there (Scamardo and Wohl 2019).
- **Noise and light pollution:** Frequent noise and constant light disturbs beavers, making many urban areas unsuitable for beaver habitation. However, this does not mean that beavers should be excluded from urban areas, with beavers thriving in urban parks across the United States (Bailey et al. 2019).
- **Little to no water:** The benefits that beavers provide in arid regions are especially valuable, including their ability to promote aquifer recharge, contribute to arid wetlands, and reduce evaporation rates. However, as rising temperatures and droughts alter the arid landscape, many areas have become unsuitable for beavers. Intermittent streams with little flow are seldom used by beavers (Gibson and Olden 2014). BDAs and rock detention structures are a viable alternative to help restore arid environments.

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?
The Beaver Restoration Guidebook	Guidebook	2023	US Fish and Wildlife Service, US Department of Agriculture Forest Service (USFS), National Oceanic and Atmospheric Administration, University of Saskatchewan	National	This comprehensive guide covers beaver ecology and beaver management strategies. The authors also provide detailed technical guidance on BDAs, urban beaver management, relocating beavers, and managing beaver habitat.	✓	✓	✓	✓
Mimicking and Promoting Wood Accumulation and Beaver Dam Activity with Post-Assisted Log Structures and Beaver Dam Analogues	Book chapter	2019	Utah State University Restoration Consortium	National	Focusing on the technical aspects of building BDAs, this guide walks practitioners through the steps of building a BDA. Filled with helpful diagrams and pictures, the geomorphic and hydrologic implications of beaver management are also discussed.	✓	—	—	✓
Low-Tech Process-Based Restoration of Riverscapes: Design Manual	Guidebook	2019	Utah State University Restoration Consortium	National	This guide explains how beaver management fits into larger river and stream restoration projects. Topics covered include designing BDAs, implementing projects, and restoring river health.	✓	—	✓	✓
Managing for Large Wood and Beaver Dams in Stream Corridors	Guidebook	2019	USFS	National	Beavers are an integral part of stream ecology, but also can create hazards. This helps managers mitigate hazards while maximizing benefits from beavers by analyzing mitigation measures and reintroduction strategies.	✓	✓	✓	✓

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Habitat Considerations at Beaver Restoration Sites: Implications for Beaver Restoration Projects	Journal article	2019	Torrey D. Ritter, Claire N. Gover, and Lance B. McNew	National	The authors analyze environmental factors that make a beaver restoration project successful. By studying wild beaver colonies, the authors recommend ideal sites for beaver habitation.	—	✓	—	—
Beaver (Castor canadensis)	Book Chapter	2003	Bruce W. Baker and Edward P. Hill	National	Providing an overview of beaver ecology and conservation, this chapter is meant for those looking for general information about beavers. Topics covered include habitat requirements, disease, beaver–fish interactions, and the economic value of beavers.	✓	—	—	—
Beaver Restoration Assessment Tool (BRAT)	Model	2013	Utah State University Ecomorphology and Topographic Analysis Laboratory	National	The BRAT model was designed to help restoration practitioners assess the feasibility of beaver management. It predicts where beavers can build dams and potential risks of beaver restoration. A fact sheet is also available.	—	✓	—	—
A Review of Two Novel Water-Tight Beaver Dam Analogs (WTBDA) to Restore Eroded Seasonal Creeks in Drain Tile Zones, to Permanent Beaver Wetlands	Article	2022	The Beaver Institute	National	This guide describes BDAs designs, including a berm and log spillway. The author weighs the tradeoffs between different designs, including management implications and costs.	✓	—	—	✓

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Drought mitigation:** Beavers can turn intermittent washes into perennial streams by spreading out runoff flow over longer periods of time. By pooling water, beavers can increase groundwater storage and aquifer recharge. Surface water preserved by beaver dams and retained during droughts allows for farmers to continue irrigating their crops (Moore and McEvoy 2022).
- **Reduced flooding:** Beaver dams are highly effective at attenuating floodwaters. When excess water flows encounter a beaver dam, the water is pushed out laterally into the floodplain, protecting downstream communities. This increases flood lag times, distributing the amount of water that a river handles over a long period of time (Puttock et al. 2021).
- **Carbon storage and sequestration:** As ecosystem engineers, beavers promote carbon sequestration by creating peatlands and other inland wetlands that function as large carbon sinks. Furthermore, beaver dams trap sediments that increase the carbon density in the soil. Beaver-modified landscapes also promote additional plant growth, facilitating the storage of carbon in woody biomass (Johnston 2014).
- **Reduced wildfire risk:** Beaver dams store water in the surrounding environment, providing water to riparian vegetation during times of drought. During wildfires, beaver-occupied riparian areas exhibited increased fire resistance compared to beaverless streams. This creates refuges for plants and animals during fires (Fairfax and Whittle 2020).
- **Heat mitigation:** During heat waves, beaver dams help keep the water temperature of streams cooler. The increased water storage from dams resulted in decreased stream temperatures, reducing mortality rates for aquatic organisms (Dittbrenner et al. 2022). Furthermore, beavers and BDAs result in lower air temperatures. Beaver dams provide water to support increased vegetative cover, which has a cooling effect on the environment (Pearce et al. 2021).

Social and Economic

- **Aquifer recharge:** Beaver dams increase the residence time for water pooling behind the dam, facilitating percolation into aquifers. Beaver dams also push water into riparian areas, increasing the surface area covered by water, allowing more water exchange points with the aquifer. Additionally, beaver dams can reduce the rate of water table drawdown during dry seasons by increasing water flows to riparian areas. The community of vegetation created by these wet conditions reduces evapotranspiration rates, allowing plants to store surplus water (Westbrook et al. 2006).
- **Resilient fisheries:** Beaver dams provide a multitude of benefits for fish, including the creation of more complex habitats, enhancing overwintering habitat, providing

cover from predators, increasing invertebrate productivity, and creating a temperature refuge. All these factors contribute to higher fish growth rates and greater fish health (Kemp et al. 2012).

- **Jobs:** For most aspects of beaver restoration, workers will have to be hired to perform the restoration activities, stimulating the local economy.
- **Mental health and well-being:** Beaver restoration improves greenspace, boosting residents' mental health and psychological well-being.
- **Tourism:** Beaver reintroductions have been shown to increase local tourism. Businesses created to support wildlife tourism help diversify the local economy and an influx of wildlife watchers may increase visitation to parks (Auster et al. 2020).
- **Cultural values:** Beavers are enigmatic animals that are intertwined with human cultural traditions. Restoring beavers to their historical range will facilitate an increased understanding of beavers (Thompson et al. 2021).
- **Reduced erosion:** Streambed erosion occurs when sediment is transported away faster than new sediment is deposited. While beaver dams may cause lateral erosion of streambanks as a result of the widening of the watercourse, this results in more sediment entering the stream, reducing streambed erosion. The beaver dam then stops the sediment from traveling downstream, nourishing the streambed with sediment (Pollock et al. 2014).

Ecological

- **Supports wildlife:** Beavers create a diversity of wetland habitats, increasing habitat for wetland species and rewet wetlands that were anthropogenically drained, allowing for the restoration of the ecosystem services these wetlands provide. Beaver dams also create wetlands at diverse successional stages, with older beaver dams hosting mature wetlands while newly built dams support emerging wetlands (Bush et al. 2019). Periodic flooding behind beaver dams creates a mosaic of habitats. Wetlands, ponds, meanders, fens, and off channels are all created by beaver dams, creating habitat for flora and fauna that rely on these special conditions for survival (Sundell et al. 2021).
- **Enhanced biodiversity:** Beavers create a wide variety of habitats, increasing the number of organisms that can live in a certain area. An increase in the diversity of birds and invertebrates has been seen in streams after beavers moved in (Hood et al. 2021; Nummi and Holopainen 2020). Beavers also increase fish biodiversity as they create a spectrum of deep-to-shallow channels, which support more fish species (Smith and Mather 2013). While it could be assumed that beavers degrade riparian areas because of their use of riparian vegetation, beaver presence actually improves riparian health. Beavers slow down water flow, reducing erosion of riparian areas. Water pooled behind beaver dams helps the water table rise, allowing riparian plants better access to water. Additionally, beavers remove more established upland trees, helping riparian plants get established themselves (Pollock et al. 2023).
- **Improved water quality:** Beaver dams capture sediment and excess nutrients behind them, improving water quality downriver. Beaver engineering also reduces

the speed of water flow, reducing suspended sediment in the water and limiting the transportation of nutrient pollution (Brazier et al. 2021). Large amounts of nutrients are stored in beaver ponds. Beavers also reduce the canopy cover in the area, facilitating plant growth and nutrient uptake from the plants which cuts nutrient runoff into waterbodies. Beavers also promote conditions ideal for denitrifying bacteria, facilitating denitrification. This is especially valuable for watersheds overloaded with nutrients from agricultural runoff (Brazier et al. 2021).

- **Increased primary productivity:** Beaver ponds increase the availability of nutrients and allow more sunlight to penetrate the water's surface, allowing primary producers to thrive. This results in an increase of primary consumers (who eat the primary producers) and creates a greater food supply for larger fish and mammals (Pollock et al. 2023).

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 beaver management and beaver analogs are included here.

- **Expense:** While beaver translocations can be relatively inexpensive, building a BDA can be quite costly (The WYldlife Fund n.d.). It can cost up to $30,000 to build a BDA, which also need frequent upkeep unless beavers move in and take over the maintenance duties (Sorflaten 2022).
- **Capacity**
- **Public opinion:** Many residents feel threatened by the presence of beavers, regardless of if threats are real or perceived. Ensuring that local stakeholders are supportive of beaver restoration efforts is critical for a successful project, as residents can easily trap the beavers, derailing the project. Research has shown that proactive engagement, appropriate communication, and shared decision-making can increase community buy in (Auster et al. 2021).
- **Conflict with other land uses**
- **Regulation:** Permitting for both BDAs and beaver translocation are complex processes given the varying levels of regulation across states. For BDAs, permits are required from multiple agencies, including the US Army Corps of Engineers, the state fish and wildlife authority, and local authorities, depending on the project jurisdiction. Additional permits will be needed if an endangered species is impacted, and the National Environmental Policy Act applies to any project on federal land or using federal money (Davee et al. 2019). Beaver translocation policies vary from state to state; the practice is illegal in some states.
- **Lack of effectiveness data**

Economic

- **Impact on timber harvest:** Beavers cut down commercially valuable trees for their dams. Flooding from beaver dams can also induce rot and disease on timber, reducing its quality and value. A single beaver dam can flood thousands of acres of low-lying forest, making it inaccessible to tree-harvesting machinery. A cost-benefit analysis of a beaver control program in Mississippi estimated that the program saved between $25 million and $57 million in timber harvest (Shwiff et al. 2011). However, alternatives to beaver trapping exist, including protecting trees with mesh and paint (Pollock et al. 2023).

- **Infrastructure damage:** Beavers can burrow through levees and roads, compromising their structural integrity and necessitating costly repairs (Taylor et al. 2017).

Community

- **Flooding:** While beavers are highly effective at attenuating floodwaters downstream, beavers create ponds directly behind their dams, flooding a previously dry area. This can be mitigated with flexible ponds levelers or Clemson beaver pond levelers (Pollock et al. 2023). Additionally, if a beaver dam experiences a sudden failure, then infrastructure downstream is at risk. Beaver dam failures have led to human fatalities and the destruction of roads, airports, and buildings (Taylor et al. 2017).

- **Disease:** Giardiasis, also called *beaver fever*, is an intestinal disease caused by a tiny parasite called *Giardia*. Humans can contract giardiasis from a variety of sources, including exposure to feces of other humans or animals or water contaminated with feces. Beavers are frequently blamed for giardiasis because of a few prominent outbreaks that have originated from beavers. However, transmission between humans is more common. Good hand hygiene and water treatment are solutions to giardiasis, meaning that disease risks shouldn't hinder beaver restoration (Rozell 2021).

Ecological

- **Beaver movement:** Once beavers are translocated, they do not stay put, with most beavers moving around 10 km from their release site. Movement is often attributed to beavers looking for a mate, suitable habitat, and their own territory; beaver movement is highly variable based on the availability of suitable habitat. The majority of beaver movement occurs within 60 days of release, as beavers rarely migrate after they have established their territory and built a dam. Therefore, it is not certain that beavers will live in the desired restoration area (Doden et al. 2022).

- **Lack of dam building:** Beavers do not always build dams, and may instead opt to build lodges, canals, or burrows. Ecologically, this means that the benefits of beavers as ecosystem engineers may not be realized, since these benefits are associated with habitat creation via dam building. Building BDAs is a way to overcome this barrier (Pollock et al. 2023).

- **Overgrazing:** Due to the dearth of predators across America, grazing species such as moose, elk, and deer are well above their historic densities. These grazing species significantly impact riparian areas, preventing woody riparian vegetation from maturing. This is an issue for beavers because they rely on mature trees close to the water for dam building. Fencing off beaver habitat is a potential solution (Kay 1994).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Magnuson Park Constructed Wetland System Beaver Restoration	Seattle, WA	Seattle Parks and Recreation, Berger Partnership	Habitat enhancement, Clemson beaver pond leveler	12.1	14.2 million	6	A team converted a military airfield into a wetland complex with the expectation that beavers would colonize the site. Soon after, a colony of beavers arrived and further modified the wetland via dam building.	No	When the beaver dams flooded walking trails, Clemson beaver pond levelers were used to control water levels.
Zuni Beaver Restoration	Zuni Reservation, NM	Pueblo of Zuni Fish and Wildlife Department	Beaver translocation, invasive species removal, grazing management	Not provided	17 million	10	To restore a local watershed, the Zuni Tribe translocated 23 beavers. Invasive species removal, reducing grazing pressure, and reshaping channelized watercourses were also completed.	Drought	Isolated instances occurred where beavers died in traps from drowning or predation. This was reduced by checking snares daily.
Methow Beaver Project	Okanogan-Wenatchee National Forest, WA	**Bureau of Reclamation, US Fish and Wildlife Service (USFWS),** USFS, Washington Department of Ecology, Washington Department of Fish and Wildlife	Beaver translocation	Not provided	Not provided	15 (ongoing)	Beavers are translocated from areas where they are deemed nuisances to streams within the natural forest. The driving force behind the project has been to restore salmon fisheries, which have been impacted by declining snowpack runoff.	Drought	The project maintains a beaver solutions hotline where they help address human–beaver conflicts.

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Cucumber Gulch Beaver Restoration	Breckenridge, CO	Town of Breckenridge, Breckenridge Ski Area	Habitat restoration, sediment removal, BDA construction, beaver translocation	2.4	Not provided	3	A ski resort significantly altered the local hydrology, with artificial snowmelt overwhelming the watershed and causing beavers to leave the area. Workers built BDAs, restored wetland hydrology, and removed excess sediment.	Flood protection	Extensive monitoring has shown that the project was a success, with natural migrants joining translocated beavers at the site and maintaining the BDAs.
Thompson Creek Beaver Restoration	Newman Lake, WA	**USFWS,** The Lands Council, Spokane Conservation District, Gonzaga University	BDA construction	65	Not provided	3	To restore Thompson Creek, the team designed and built more than 18 BDAs. This also helped restore the floodplain surrounding Thompson Creek.	No	Thompson Creek was a major source of phosphorus pollution for Newman Lake, which had issues with harmful algae blooms. Previous efforts to reduce the pollution had failed. The team then turned to BDAs, which slowed phosphorus flow.

Bolding indicates DOI affiliates.

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Riverine Habitats
22. Floodplain Reconnection

DEFINITION

A *floodplain* is a low-lying area directly adjacent to a waterbody and partially or fully flooded during high-water events (Demek 1988). Generally located on the floor of a river valley, floodplains provide a natural inundation area that aids with water retention during high flows. The ecology of a floodplain primarily consists of herbaceous vegetation, with peat bogs, streams, lakes and small stands of forest interspersed. All floodplain habitats are reliant on ample water for their ecological processes (Krizek 2006). Across the United States, development has resulted in disconnections between floodplains and their adjacent waterbodies (primarily rivers). Engineered river channels, levees, berms, channel straightening, dam construction, and high levels of water withdrawal are all drivers of floodplain disconnection (Loos and Shader 2016). Floodplain reconnection, also referred to as *floodplain restoration*, can take a variety of forms including dam removal, levee removal or setback, the aggradation of mainstem channels, restoration of floodplain habitat, and culvert replacement or removal (Pess et al. 2005).

TECHNICAL APPROACH

The following strategies are used in floodplain reconnection projects to reverse anthropogenic alterations of a floodplain:

- **Dam removal:** Increasingly, dam removal has been used as a floodplain reconnection technique. Dams alter nutrient cycling, impact the deposition of sediment, reduce flood frequency, and limit the range of migratory aquatic species, all of which reduce floodplains' ecological health (Bednarek 2001). Dam removal techniques vary. Often, water is diverted before dam removal so that the dam can be deconstructed "in the dry." Alternatively, dams can be deconstructed "in the wet," where the dam is slowly lowered over an extended period to allow the riverine system time to adjust to the new water flows (American Rivers 2023). The impacts of dam removal are immense and affect the whole riverine system, not just floodplains (Bednarek 2001).
- **Levee removal or setback:** Levee setback projects allow rivers to migrate and create different floodplain channel types. Given the space constraints on floodplains in developed areas, levees can be set back instead of completely removed to protect nearby property from floods (Figure 1). Levee setback and removal is often paired with floodplain restoration habitat projects (descriptions follow), given that they create additional space for wildlife habitat (Pess et al. 2005).
- **Installing submersible check dams and logjams:** Submersible check dams and logjams are meant to reconnect relic channels or disconnected meanders back to the main river channel (Cowx and Welcomme 1998). *Logjams* are large piles of timber

Figure 22.1 Construction equipment traverses a new setback levee to remove material from the old levee along the Sacramento River

Photo courtesy US Army Corps of Engineers

that often accumulate in floodplains after being carried from upriver during floods. Gathering logs in a central location can help aggrade mainstem channels and create new habitat (Roni et al. 2019). Submersible check dams help facilitate the aggradation process as well as slow the velocity of the water (Pess et al. 2005).

- **Culvert replacement or removal:** Culverts and other stream passages limit connection within a floodplain. Flows of wood, sediments, nutrients, and fish become better distributed throughout the floodplain when culverts are removed or upgraded (Roni et al. 2002).
- **Construction of side and off channels:** Creating side channels allows for nearby ponds and wetlands in the floodplain to be connected to the primary river (Figure 2). These arteries can serve as vital breeding grounds for salmon (Pess et al. 2005).

Once the hydrological, geological, and chemical processes of the floodplain have been restored, habitat restoration is usually also performed to help jump-start natural processes. This usually involves planting native species. Micromanipulation of topography is also common to provide habitat for specific species, such as spawning grounds for salmon (Pess et al. 2005).

Figure 22.2 Constructed channel with reconnected floodplain at Black Forest Creek, CO

Photo courtesy USFWS Mountain-Prairie

OPERATIONS AND MAINTENANCE

Following floodplain reconnection, it is important to clear invasive vegetation and excessive understory vegetation in the restored floodplain. After heavy rains, logjams and submersible check dams should be inspected and repaired if needed. Side channels will need to be periodically redredged to maintain their connection to the main channel.

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Slope of terrain less than 6%:** Floodplains need to be flat to adequately hold excess water. High gradients along the river will channel more runoff into the river instead of reducing the peak water flow (Rosgen 1994).
- ✓ **Near-natural river flow**: A floodplain must be adjacent to a river with near-natural flow conditions to receive periodic inundations of water. Inland waterbodies independent of riverine systems are generally classified as wetlands (see strategy summary).

- ✓ **Close to gravel pits or other anthropogenic water retention infrastructure:** Gravel pits have been identified as critical habitat for many riparian species, especially amphibians. This allows for increased habitat connectivity for these species (Rhode et al. 2006)
- ✓ **Ample space between infrastructure and the river:** Roads, industrial parks, and housing complexes are often located close to rivers. Attempting to restore a floodplain in developed areas increases flood risk for the community. Structures should be moved as part of a managed retreat strategy or floodplain restoration should be sited elsewhere.
- ✓ **Within 10 km of an established floodplain:** An already functioning floodplain near a restoration site facilitates the colonization of the restored site by local flora and fauna. It is preferable if the established floodplain is upstream of the restored site, given that many organisms use the river flow to aid their movement (Rhode et al. 2005).
- ✓ **High levels of nutrient pollution due to nearby agricultural runoff:** Like riparian buffers, floodplains can block nutrient pollution from entering a river. Floodplains often replace farmland formerly sited too close to the river, which discharged excess fertilizer into the river when the fields were inundated (Ribarova et al. 2008).
- ✗ **Significant riverbed erosion:** Riverbed erosion is an indicator that sediment transport is being blocked. A lack of sediment will hinder the creation of natural floodplain components such as sandbars and transient islands (Rhode et al. 2006).
- ✗ **Close to a dam that will not be removed as part of the project:** Dams function as sediment retention basins, blocking sediment from moving downstream. Dams also limit water flow to downstream floodplains and permanently flood upstream areas, disrupting the natural inundation cycles that make floodplains successful.
- ✗ **In a densely populated urban area:** Floodplains need significant space, and this space is often not available in densely developed urban areas.

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?
Floodplain Restoration Resources	Website	2023	American Rivers	National	Website with links to more than 20 resources relating to floodplain reconnection. These include handbooks on floodplain reconnection, using nature to mitigate flood damage, and floodplain planning strategies.	✓	✓	—	✓
Central Valley Flood Protection Plan	Guidebook	2022	California Department of Water Resources	California	Document that lays out steps planners have taken to manage floodplains in California's Central Valley. This resource includes case studies on levee setback, flood management equity, and incorporating climate change into floodplain planning.	✓	—	✓	—
Project Management Resources	Website	2023	Floodplains by Design	Written with an emphasis on Washington state but most of the information is more broadly applicable	Website with links to resources about floodplain management collaboration, permitting through the US Army Corps of Engineers (USACE), and managing contractors. The site also provides resources tailored toward tribal projects, communication, and monitoring mechanisms.	✓	—	✓	—
State of Vermont Flood Ready—Use Natural Flood Protection	Website	2013	State of Vermont	Designed for Vermont but most of the information is more broadly applicable	Overview webpage outlining the new paradigm of nature-based floodplain management. This resource links to case studies, technical guides, and videos pertaining to floodplain reconnection.	✓	—	—	✓

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Association of State Flood-plain Man-agers Flood Resource Library	Website	2023	Association of State Flood-plain Managers (ASFPM)	National	This library contains a diverse array of resources pertaining to floodplain management, including technical reports and gov-ernment documents. The li-brary also holds the research of the Flood Science Center, a branch of the ASFPM.	✓	—	✓	✓
Inter-Fluve Floodplain Reconnection Atlas	Website	2020	Inter-Fluve	National	Collection of case studies containing past floodplain reconnection projects, in-cluding habitat restoration and side channel creation. At the bottom of the page, Inter-Fluve also has informa-tion for related nature-based solutions (NBS) such as dam removal, large log design, and off channel habitat res-toration.	—	—	—	✓
Connecting Rivers to Floodplains	Guidebook	2016	American Rivers	National	This guidebook describes how to perform a floodplain reconnection project in four easy-to-follow steps. This resource also provides characteristics of a func-tional floodplain to provide a standard for successful projects.	✓	—	—	—

GRAY INFRASTRUCTURE ALTERNATIVES

Floodplain reconnection can be an alternative to several gray infrastructure approaches designed to address riverine flooding: dam construction and levee/dike systems. The ability of a floodplain reconnection 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 floodplain reconnection. See the gray infrastructure alternative tables in Section 1 for a comparison of floodplain reconnection to these alternatives.

LIKELY BENEFITS AND OUTCOMES

Climate Threat Reduction

Primary objectives for each strategy are highlighted.

- **Reduced flooding:** Floodplain reconnection can reduce the peak velocity of water by establishing alternative routes for the water to flow (side channels, ponds, meanders, and so on), reducing the load on the main channel of the river (FEMA 2015). Floodplain reconnection frequently entails levee setbacks or removals, giving floodwaters a greater area to disperse over and reducing the flow of water entering individual communities (NRC Solutions 2023).
- **Drought mitigation:** Floodplains facilitate groundwater recharge by providing greater surface area to percolate for floodwater to percolate into belowground aquifers. Reconnected floodplains are highly effective at retaining water during flash floods (American Rivers 2023). Instead of the water being washed downriver, the water recharges aquifers, helping store water for future droughts (FEMA 2015).
- **Heat mitigation:** Temperatures within a floodplain can vary significantly, with exposed sediments considerably hotter than aquatic or forested habitats (Tonolla et al. 2010). Floodplain reconnection enhances and expands both the vegetation cover and water flow within a floodplain. Therefore, reconnected floodplains help reduce both water and surface temperatures during heatwaves (ASFPM 2023).
- **Reduced wildfire risk:** Because floodplain reconnection increases the diversity of habitats across a floodplain, it creates greater heterogeneity in burn severity during a fire, also called *pyrodiversity* (Jones and Tingley 2021). As a result, floodplains are better able to serve as a fire break and reduce the chance of a large wildfire jumping across the river. Increased pyrodiversity also enhances biodiversity as the floodplain recovers from the wildfire, creating new ecological niches (Pugh et al. 2022).
- **Carbon storage and sequestration:** Reconnected floodplains have been shown to sequester greater amounts of CO_2 than degraded ones (Craft et al. 2018).

Social and Economic

- **Reduced erosion:** Healthy floodplains help reduce erosion during extreme floods. Floodplains are natural regulators of sedimentation, helping redistribute excess sediment throughout a river system (Ahilan et al. 2016).

- **Property and infrastructure protection:** By restoring the natural floodplain, reconnection reduces the height of floodwaters. As a result, floods are less likely to penetrate nearby levees and infiltrate local communities (NRC Solutions 2023).
- **Agriculture and timber yields**: Reconnected floodplains protect nearby agricultural areas from floods, provided that the agricultural areas are far enough away from the river. Additionally, floodplains improve water quality, pollinator habitat, and aquifer recharge rates, all of which increase agricultural yields (TNC 2018).
- **Mental health and well-being:** Floodplains can serve as public green space, which helps improve residents' mental health.
- **Recreational opportunities:** Floodplain reconnection makes an area more suitable for a plethora of recreational activities, including kayaking, birdwatching, and fishing.
- **Jobs:** Workers will need to be hired to perform the restoration activity, boosting the local economy.
- **Increased property values:** Floodplain reconnection has been shown to increase nearby property values, potentially because of reduced flood threats to the property (Gourevitch et al. 2020).
- **Cultural values:** Floodplain reconnection can increase local knowledge of the ecosystem and provide aesthetic values that increase sense of place.
- **Resilient fisheries:** Reconnected floodplains provide ideal spawning grounds for migratory fish species like salmon, aiding both inland and coastal fisheries (Pess et al. 2006). Floodplain reconnection also can entail dam removal, which improves passage for migratory fish species.

Ecological

- **Improved water quality:** Reconnected floodplains can absorb greater quantities of sediment, nutrient pollution, and toxins thanks to the ability of native vegetation to filter water. As a result, healthier floodplains can reduce hypoxic zones and algae blooms downstream and help to prevent bioaccumulation and biomagnification of toxins in seafood (Grift 2001; Craft et al. 2018; TNC 2018).
- **Enhanced biodiversity:** Floodplain reconnection has been shown to increase the number of microhabitats interwoven within a floodplain, increasing overall biodiversity (Mount 2011).
- **Supports wildlife:** Floodplains slow down water flows, creating conditions for higher primary productivity among zooplankton. This increase of biomass at lower trophic levels supports higher native fish populations (Mount 2011).
- **Increased habitat connectivity:** Floodplain reconnection provides lateral connectivity from the main channel of the river to various ecological niches throughout the floodplain via the creation of side channels (Opperman et al. 2010).

BARRIERS AND SOLUTIONS FOR PRACTITIONERS

Common Barriers

- Several barriers are common across many of the NBS strategies; these are described in more detail in Section 1 of the Roadmap. Additional notes about the barriers specific to floodplain reconnection are included here.
- **Expense:** While the costs of floodplain reconnection projects can be low compared to flood damage expenses, the upfront costs of reconnection are still high (Gourevitch et al. 2020). This is especially true when large infrastructure adjustments are involved. For example, a levee setback project in West Sacramento, CA, carried a price tag of $20 million per mile (NRC Solutions 2023).
- Capacity
- **Public opinion:** While floodplain buyouts compensate residents for their property at market value, this does not account for the costs of relocating and adjusting to a new community. Community members are usually unwilling to move out of an area to make way for floodplain reconnection (Lipuma 2021).
- **Conflict with other land uses:** Agricultural or urban areas are frequently sited in floodplains, meaning that certain structures and fields may have to be removed for reconnection (Brouwer and van Ek, 2004). This is usually done through floodplain buyouts, which can be expensive and are voluntary, so a project may not be feasible to complete if property owners are not willing to sell (Lipuma 2021). Floodplain reconnection may also reduce the navigability and straightness of a waterbody for use as a shipping corridor.
- **Regulation**
- **Lack of effectiveness data**

Community

- **Legal:** River flow may not be able to be altered because of water rights or other legal issues (Loos and Shader 2016).
- **Safety:** Levee setbacks or dam removals may not be possible because of engineering difficulties or flood safety concerns (Loos and Shader 2016).

Ecological

- **Habitat disruption:** Riverbed incision, where the riverbed drops a few meters because of dam removal, may disrupt sensitive habitat (Loos and Shader 2016, Maaß and Schüttrumpf 2019).
- **Nutrient pollution:** Fertilizer runoff from nearby agricultural fields may overwhelm the ability of the floodplain to filter nutrient pollution and cause ecosystem collapse.
- **Invasive species:** Floodplains are prone to being overrun by invasive species. Invasive species have been shown to limit the ability of floodplains to attenuate floodwaters. However, native species can better compete with invasives as the floodplain is more frequently inundated (Hutchinson et al. 2020).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Salamander Parcel Floodplain Reconnection	Douglass County, OR	**US Fish and Wildlife Service (USFWS),** the Confederated Tribes of the Siletz Indians	Dike removal, channel reconstruction	41 acres, 8 stream miles	200,000	Not provided	Old roads and dikes were removed to allow water to reach the floodplain. Channels were reconstructed to allow fish to access the floodplain as well.	Inland flooding	Indigenous Knowledges from the Confederated Tribes of the Siletz Indians was used to help restore fisheries.
Pocomoke River Floodplain Restoration Project	Southeastern Maryland	**USFWS**, Maryland Department of Natural Resources, US Department of Agriculture, The Nature Conservancy (TNC), **US Geological Survey**	Levee breach at selected locations	3,000 acres, 9 river miles	1 million	3 years	Contractors breached a levee in more than 100 spots to allow water to reach the adjacent floodplain.	No	Conservation easements were negotiated on many of the parcels in the floodplain to avoid costly floodplain buyouts.
Green River Reconnection Project	Ouray National Wildlife Refuge, UT	**USFWS, Bureau of Reclamation**	Levee breach at selected locations	800 acres	234,800	3 months	To connect wetlands to the main channels of the Green River, a levee was breached at several locations to let floodwaters come through.	Drought	Hydrodynamic modelling was used to help create an effective restoration plan.
Steigerwald Reconnection Project	Steigerwald National Wildlife Refuge, WA	**USFWS,** National Oceanic and Atmospheric Administration, Bonneville Power Administration	Side channel creation, infrastructure relocation, levee setback	965 acres	32 million	3 years	Contractors installed large wood habitat structures, treated invasive species, reforested an alluvial fan, removed current levees and built levee setbacks.	Inland flooding	The project eliminated the need for pumps to protect a nearby industrial park and wastewater treatment plant.

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Redwood Creek Restoration Project	Golden Gate National Recreation Area, CA	**National Park Service (NPS)**	Levee removal, infrastructure relocation, bridge renovation, invasive species management, revegetation	42 acres, 1,700 linear feet of stream	1.76 million	2 years	Workers removed a levee and artificial fill from the floodplain to restore the natural hydrology. Because the area is popular with visitors, a parking lot and trails had to be reconfigured. Hillsides were also revegetated to prevent erosion.	Inland flooding	Side channels and ponds were built to serve as spawning grounds for coho salmon.
Elwha Floodplain Restoration Project	Olympic National Park, WA	**NPS,** Lower Elwha Klallam Tribe, **Bureau of Reclamation**	Dam removal, logjam construction, culvert correction	715 acres, 70 river miles	324.7 million	4 years	This project is the largest dam removal project in history, allowing floods to reach the Elwha River's floodplain after more than 100 years of damming. Two dams were removed and the floodplain was enhanced with new culverts and logjams.	Inland flooding	The project greatly impacted sedimentation throughout the river, restoring the delta of the Elwha River.
Mollicy Farms Floodplain Restoration Project	Upper Ouachita National Wildlife Refuge, LA	**USFWS,** TNC	Levee removal and revegetation	16,000 acres, 17 river miles	4.5 million	1 year	A levee was breached to reconnect a historic floodplain to the Ouachita River. The forest in the floodplain was also replanted.	Inland flooding	While the project was still in the planning phase, the levee was naturally breached by historic floods. Managers adapted their plan to widen already existing breaches and create new ones.

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Sacramento-to-Kern Rivers Floodplain Reconnection Project	Sacramento National Wildlife Refuge, CA	**USFWS,** USACE, TNC, **Reclamation**	Levee removal, floodplain buyouts, and habitat restoration	1,400 acres	1.37 million	Not provided	Managers purchased orchards that had been built in the floodplain protected by a levee. They removed the levee, restored native vegetation, and built a levee setback.	Inland flooding	The project was initiated after fixing the levee was deemed too expensive.

Bolding indicates DOI affiliates.

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Riverine Habitats
23. Riparian Buffer Restoration

DEFINITION

Riparian buffers are vegetated areas adjacent to an inland waterbody that are managed to protect the waterbody from the impacts of surrounding land uses (USFS n.d.). Riparian buffers can consist of a combination of trees, shrubs, and grasses that extend parallel to the banks of the waterbody. Spanning residential, agricultural, industrial, and natural land uses, riparian buffers prevent excess nutrients, sediments, and pollutants from entering the waterbody (Luo et al. 2017). Riparian buffers, generally located on steep slopes, are often installed because of their effectiveness at mitigating erosion compared to stone or concrete banks (Kenwick et al. 2009). Riparian buffers are under threat from invasive species, channelization, overgrazing, conversion to agricultural or urban land uses, and increased wildfire severity (Theobald et al. 2010). Restoring riparian buffers involves regrading stream banks, removing invasive species, installing grade control structures, reconfiguring channels and replanting native species (Laub et al. 2013).

TECHNICAL APPROACH

Restoring riparian buffers involves remediating changes to the soil, hydrology, and geomorphology in and around a riverine system.

1. **Restoring waterway hydromorphology:** The following techniques are commonly used to restore the hydromorphic properties of the stream or river:
    - **Regrading stream banks:** Stream or riverbanks at steep gradients are more prone to erosion and less conducive to vegetation growth. Regrading stream banks involves manipulating the soil to create a flatter slope adjacent to the waterbody, often using heavy machinery. This also typically involves moving the banks back from the waterbody, giving the water more room to flow following heavy precipitation events (Laub et al. 2013).
    - **Invasive species removal:** Riparian buffers are particularly vulnerable to being overtaken by invasive species because they are often sandwiched between developed areas. The dearth of adjacent intact ecosystems aids the proliferation of invasives, primarily herbaceous shrubs and vines (Johnson et al. 2020). Control strategies must be targeted towards individual species, with common control mechanisms including chemical (herbicides), biological (introducing predators), and mechanical (physically removing the plants) controls (USDA n.d.).
    - **Installing grade control structures:** A *grade control structure* is an earthen, wooden, or concrete structure that helps prevent streambed erosion and regulates the velocity of water flow (Cobb and Rainwater 2013). While grade control structures are in the riverbed and not the buffer, they can help riparian restoration by directing water away from eroded banks.

- **Reconfiguring channels:** Many degraded riparian buffers abut channelized streams, where the natural shape of the stream has been straightened. Restoring dynamic channels, which are self-sustained by the processes of sediment transport, creates more resilient riparian buffers that are less likely to erode. To do this, artificial bed substrates must be removed, peak inflows from stormwater drainage systems must be reduced, and riverbanks must be adjusted to restore natural meanders (Vietz et al. 2016).
- **Removing anthropogenic barriers:** Levees line many rivers and streams to keep the water flow within one channel. Because levees are directly adjacent to a river, they occupy the space where a riparian buffer would normally be. Levees have steep slopes and limited vegetation cover, and thus do not support riparian ecological processes (Griggs 2009). Heavy machinery is generally needed to remove levees or other anthropogenic barriers along rivers.
- **Installing natural materials:** To secure banks and mimic natural riparian habitat, boulders and wood are often placed along riverbanks. These abiotic components provide habitat for many amphibian species and help prevent erosion (Norris 1970).

2. **Vegetative restoration:** Once hydromorphic properties of the river or stream have been restored, native species are planted (Figure 1).

   Riparian buffers consist of different zones of flora based on their proximity to the waterbody. Closest to the water is the *emergent zone*, where small, hardy pioneer species should be planted. Next is the *mesic zone*, which is dominated by shrubs and smaller understory trees. Above that is the *xeric zone*, where mature trees are established and provide shade to the other zones (Bair et al. 2021). Outside of the xeric zone is a strip of woody florals and herbaceous forbs, which serve as the first line of defense against runoff (USFS n.d.). Installing plants in riparian buffers can be difficult because of the steep slopes. The following techniques may help:

   - **Wattle fences:** *Wattle fences* are walls of live cuttings built along terraces. The terraces help stabilize the bank until the cuttings develop roots and grow (Polster 2002).
   - **Live bank protection:** Similar to wattle fences, *live bank protection* is a wall of live cuttings that extends along the contours of a stream, preventing erosion (Polster 2002).
   - **Live palisades:** The live palisades technique involves sticking cuttings of larger trees into the ground like posts. The roots will overlap and form a web that will protect the soil (Petrone and Preti 2010).
   - **Live gravel bar staking:** In areas with large gravel deposits, cutting can be wedged in between rocks to help secure the bank. It is important that the cutting reach all the way down into the substrate (Polster 2002).

For areas with low gradients and minimal erosion, more conventional techniques such as planting plugs or scattering seeds can be used.

Figure 23.1 Planting sedges and rushes along Kettle Creek, CO

Photo courtesy USFWS Mountain-Prairie

OPERATIONS AND MAINTENANCE

Trash and debris will need to be removed from the restored riparian buffer monthly, and invasive species control may be necessary as well. Mulching and mowing are generally done on an annual basis (Cole et al. 2020). In some cases, erosion may create gullies that need to be filled in, and erosion control measures (revegetating eroded areas, using temporary erosion fences) may be required to prevent the problem from recurring.

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Adjacent to sources of nutrient pollution including golf courses, agricultural fields, pastures, or residential areas:** One of the primary benefits of riparian buffers is their ability to intercept nutrient pollution before it enters the water. Locating a riparian buffer near a source of nutrient pollution will magnify these benefits (NC DENR 2004).

- ✓ **Water table depth within 3 to 4 ft of the surface:** This water table depth allows plants to access water without becoming waterlogged. This range can be determined by the soil core characteristics (NC DENR 2004).
- ✓ **Sparse or absent woody vegetation:** Sparsely vegetated banks are where riparian buffers are most needed as there is nothing there to protect the river (NC DENR 2004).
- ✓ **Near a body of water that experiences frequent flooding:** Riparian buffers can help absorb excess water before it reaches the waterbody, reducing the amount of water the river must handle. Additionally, the buffer can serve as a part of a floodplain, preventing floodwaters from reaching developed areas.
- ✓ **Banks experiencing significant erosion:** Riparian vegetation helps stabilize eroding banks, protecting property and keeping excess sediment out of the waterbody.
- ✗ **Area that has significant grazing pressure:** High grazing pressure destroys riparian vegetation and limits the success of a restoration project. If a riparian area is adjacent to a grazing pasture, a fence should be installed to protect the buffer vegetation.
- ✗ **Land around the waterbody is constrained by other uses:** In many urban areas, development occurs right up to the river's edge (NC DENR 2004). Moving infrastructure for a riparian restoration project is generally impractical.
- ✗ **Site is seldom wet and handles small amounts of runoff:** In terms of prioritization, sites that are seldom wet and do not handle runoff would limit the benefits a restoration project would yield. While riparian vegetation would not cause any negative environmental impacts at these sites, it is best to choose areas with the greatest need for buffers to maximize scarce resources (Russell et al. 1997).
- ✗ **Channel with an artificial substrate (concrete, brick, and so on) that won't be removed as part of the project:** In many urban streams, the natural bed substrate has been replaced by an artificial riverbed. This alters the hydrology of the stream and is not compatible with a riparian buffer.
- ✗ **Slope greater than 6% (unless being regraded as part of the project):** Plants often struggle to establish themselves on steep slopes. Furthermore, steep slopes are more prone to erosion and degradation (NC DENR 2004).

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?
Riparian Restoration	Guidebook	2004	US Department of Agriculture Forest Service (USFS)	National	Written for technicians restoring riparian ecosystems, this guide overviews the design of riparian restoration projects for areas that are impacted by recreation. Topics covered include pest management, monitoring, planting techniques, and managing human impacts.	✓	✓	✓	—
California Riparian Habitat Restoration Handbook	Guidebook	2009	California Riparian Habitat Joint Venture	Written for California but most of the information is more broadly applicable	This guide puts an emphasis on restoring the hydrology of the river as the key to riparian restoration. The author provides guidance for designing projects in watersheds altered by levees, dams, and logging practices.	✓	✓	✓	—
Riparian Buffer Restoration	Book Chapter	2006	Pennsylvania Department of Environmental Protection	Written for Pennsylvania but most of the information is more broadly applicable	The authors lay out a simple framework for planning and installing riparian restoration projects. With a focus on maintenance, other topics covered include design considerations and planting in developed environments.	✓	✓	—	—
A Field Guide to Riparian Restoration, and Upland and Arroyo Erosion	Guidebook	2021	Watershed Management Group	Arid regions	Erosion is a significant issue in arid regions that receive large downpours, a problem this guide seeks to rectify. The authors describe a variety of techniques to retain water, reduce channel incision, and restore buffers.	✓	✓	—	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Guidelines and Protocols for Monitoring Riparian Forest Restoration Projects	Guidebook	2011	New Mexico Forest and Watershed Restoration Institute	Southwest United States	This guide details the process of monitoring riparian restoration projects. The authors explain the reasoning behind monitoring, what to monitor, and monitoring techniques.	—	—	✓	—
Restoring Riparian Ecosystems	Book chapter	2020	Washington Department of Fish and Wildlife	Pacific Northwest	This chapter of a larger management manual covers riparian restoration, outlining suggested riparian restoration techniques. Additional topics include monitoring strategies, adaptive management, and regulatory considerations.	✓	✓	✓	—
Chesapeake Bay Riparian Handbook: A Guide for Establishing and Maintaining Riparian Forest Buffers	Guidebook	1998	USDA	Designed for the Chesapeake Bay watershed but most of the information is more broadly applicable	This guide goes through a variety of factors that need to be taken into consideration when restoring a riparian buffer, including soil quality, buffer width and streamside stabilization. The authors describe the relationship between riparian buffers and their surrounding land uses, including forestry, agriculture, and urban development.	✓	✓	—	—
Case Studies of Riparian and Watershed Restoration in the Southwestern United States—Principles, Challenges, and Successes	Guidebook	2017	US Geological Survey (USGS)	Southwest United States	Spanning restoration techniques and a variety of case studies, this guide catalogs the challenges and successes of riparian restoration in the Southwest United States. By exemplifying the lessons learned from each project, the authors aggregate collective knowledge on riparian restoration.	✓	✓	—	✓

GRAY INFRASTRUCTURE ALTERNATIVES

Riparian buffer restoration can be an alternative to gray infrastructure approaches that address riverine flooding (levee and dike systems) or urban runoff (stormwater drainage systems). The ability of a riparian buffer restoration project to replace or supplement these gray infrastructure approach 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 riparian buffer restoration. See the gray infrastructure alternative tables in Section 1 for a comparison of riparian buffer restoration to these alternatives.

LIKELY BENEFITS AND OUTCOMES

Climate Threat Reduction

Primary objectives for each strategy are highlighted.

- **Reduced flooding:** During high-volume precipitation events, riparian buffers help absorb increased runoff flows into the ground before they reach the river. This reduces the volume of water the river must handle, limiting downstream flooding. Furthermore, riparian zones can attenuate excess floodwaters if a river exceeds its bank, mitigating damage to nearby properties (Hawes and Smith 2005).
- **Heat mitigation:** Riparian zones can help mitigate heat waves by decreasing both air and water temperature. Water temperature is decreased as it slows while traversing the riparian buffer before it enters the primary waterbody. Air temperature is reduced by the dense canopy cover in riparian zones (Somers et al. 2013).
- **Drought mitigation:** Riparian buffers can mitigate drought by recharging aquifers. Riparian areas slow down runoff; buffer vegetation increases soil infiltration capacity, allowing for surplus runoff to percolate into aquifers (Singh et al. 2021).
- **Carbon storage and sequestration:** Riparian buffers contain a diverse array of vegetation, from climax community trees to pioneer grasses, all of which absorb CO_2 from the atmosphere (Vidon et al. 2019).

Social and Economic

- **Reduced erosion:** Riparian buffers can help reduce erosion by providing vegetation to stabilize steep banks and prevent topsoil from entering streams (Nakao and Sohngen 2000). Furthermore, riparian buffers can provide valuable flood protection, limiting the amount of soil loss that occurs in nearby areas (Hawes and Smith 2005).
- **Mental health and well-being:** Riparian buffers can function as valuable waterfront greenspace, increasing residents' mental health and psychological well-being.
- **Cultural values:** Restoring riparian buffers can increase residents' appreciation and admiration of the local ecosystem.
- **Jobs:** Contractors will need to be hired to implement the restoration, boosting the local economy.

- **Agriculture and timber yields:** Riparian buffers help increase yields in nearby agricultural areas by providing habitat for pollinators, providing habitat for predators that help to control pests, decomposing dead organic material, and reintegrating nutrients back into the soil (Luke et al. 2019).
- **Resilient fisheries:** The presence of an established riparian buffer helps regulate the transfer of solar energy, organic materials, and inorganic materials in between terrestrial and aquatic environments, improving the conditions in which fish live and thus their health. For example, the leaf litter created by riparian vegetation improves fish habitat quality and diversity. Furthermore, when riparian buffers hinder excess nutrients from entering waterbodies, they increase the rate of fish survival (Pusey and Arthington 2003).
- **Increased property values:** Riverfront properties with riparian buffers have higher values than similar properties without (Bin et al. 2009).

Ecological

- **Improved water quality:** Riparian buffers are highly effective at intercepting excess nutrients and sediment runoff before they enter waterbodies, preserving local water quality (Anbumozhi et al. 2005; Mankin et al. 2007). Wider buffers are more effective at preventing pollutants from reaching water bodies (Ortiz-Reyes and Anex 2018). Furthermore, riparian zones help limit additional sources of sediment pollution by preventing stream banks from eroding.
- **Enhanced biodiversity:** Riparian buffers have been shown to increase biodiversity because they conserve vital habitat, especially for animals that use both terrestrial and aquatic environments at different stages in their life cycles. Buffers of 50 m can support a sufficient amount of biodiversity for most species while buffers of at least 150 m are needed to maintain bird biodiversity (Lind et al. 2019).
- **Supports wildlife:** Riparian buffers create a wide variety of riverine habitats by modifying light penetration into water, depositing woody debris, altering water flow, and protruding vegetative root masses into the water. This allows for a greater diversity of species to thrive in the same aquatic region. The canopy of a riparian buffer also moderates the transition of solar energy into the water, resulting in fewer temperature fluctuations. Consistent temperature helps a greater number of aquatic organisms thrive (Pusey and Arthington 2003).
- **Increased habitat connectivity:** Riparian buffers mirror the long and narrow morphology of the rivers they surround, meaning that they can connect distant fragments of habitat. This fosters increased species diversity, genetic diversity within species and migratory pathways (Naiman and Décamps 1997).

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 riparian buffer restoration are included here.

- **Expense**
- **Capacity**
- **Public opinion:** While floods can increase community awareness about their vulnerability without riparian buffers, a catastrophic flood soon after a riparian restoration process has commenced can sour public opinion towards the project. Although mature buffers can attenuate floodwaters, severe floods can kill young plantings before they can make a significant impact on the environment (Thomson and Pepperdine 2003).
- **Conflict with other land uses:** Successful riparian buffers are generally around 100 m wide (50 m on each side of the waterbody), meaning that significant areas of land will have to be converted from their former uses (Santelmann et al. 2001). Riparian buffers are often adjacent to grazing areas. Riparian areas cannot tolerate intense grazing pressure and the waste of grazing animals often adds excess nutrients to the waterbody, heightening the risk of eutrophication (Sovell et al. 2000). Riparian buffers also take up the space directly along the water's edge, meaning that development cannot occur there. This is problematic for many industries that need direct access to water.
- **Regulation:** Many streams in the United States, especially in arid regions, are intermittent or ephemeral. However, these channels still need riparian buffers because they are acutely prone to erosion when they are inundated by heavy rains. In light of the recent Supreme Court ruling in *Sackett v. Environmental Protection Agency,* Clean Water Act protections no longer apply to most of these waterbodies (Turrentine 2023).
- **Lack of effectiveness data**

Community

- **Overuse by visitors:** In frequently visited areas, there is a tendency for visitors to informally expand trails and campsites into riparian areas. Heavy foot traffic and trash is detrimental to riparian buffers, meaning that projects in areas with high visitation often need to be fenced (Eubanks 2004).

Ecological

- **Invasive species:** Invasive species plague riparian areas and invasive species management must be a part of routine maintenance and monitoring for any restoration project. Communities of invasive species can coexist with each other in riparian buffers, amplifying the problem (Harms and Hiebert 2006).
- **Release of in-stream sediment stores:** Polluted sediments from previous poor land use management often build up in streams (Greenwood et al. 2012). The restoration of riparian buffers has the ability to release these sediment stores, which can be mitigated by dredging or the use of fine-sediment suction devices (McKergow et al. 2016).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Granite Camp Riparian Restoration	Grand Canyon National Park, AZ	**National Park Service (NPS),** Grand Canyon Association	Invasive species removal via mechanical control, installing native vegetation via planting poles and seeding	2 acres	104,500	1 year	Granite Camp is a remote backcountry camp in Grand Canyon National Park along the Colorado River. Volunteers removed invasive tamarisk trees and replaced them with a variety of native species, including willows and cottonwoods.	Inland flooding	The backcountry setting was particularly difficult to work in because plantings had to be flown in by helicopter and transplanted using hand tools because of a wilderness designation limiting the presence of power tools.
Canyon de Chelly Riparian Restoration Project	Canyon de Chelly National Monument, AZ	**NPS,** Navajo Nation	Invasive species removal	800 acres	NA	10 months	Invasive tamarisk and Russian olive trees caused significant channel incision and erosion while also adding to the fuel load in a fire-prone, arid region. The invasive trees were removed using a backhoe. To allow the newly restored areas to recover, fences were installed to keep out grazing animals.	Drought, wildfires	The cut-stump method was found to be the most cost-effective method of removing invasive shrubs and trees.

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Las Vegas Wash Restoration Project	Clark County, NV	Southern Nevada Watershed Authority, **US Bureau of Reclamation**	Invasive species removal, native plant installation, building grade control structures	1,400 acres	125 million	13 years	To reduce the erosion and sedimentation of the Las Vegas Wash, workers built grade control structures to slow down the water in this ephemeral channel. A host of invasive species were removed and replaced with native vegetation to stabilize the banks.	Inland flooding, drought	Supplemental irrigation was needed to support plants in this arid region.
Fourmile Creek Fish Passage Restoration Project	Klamath County, OR	**US Fish and Wildlife Service, USGS,** US Department of Agriculture Forest Service (USFS), Klamath Bird Observatory	Debris removal, removing anthropogenic barriers, restoring historic channels, large wood and boulder placement	2 acres	172, 763	5 years	To divert a channel through its original riparian habitat, workers removed gradient barriers and debris. Large wood and boulders were also used to mimic natural riparian habitat.	No	Removing debris was critical to reducing sediment buildup plaguing the stream.
Beaver Creek Restoration Project	Helena -Lewis and Clark National Forest, MT	USFS; Montana Fish, Wildlife and Parks; Trout Unlimited	Installing natural materials, seeding native plants, planting native trees, constructing pools	1.2 creek miles	462,590	3 years	Volunteers helped restore the riparian zone around Beaver Creek by creating natural meanders with large wood and constructed pools. Native plants were also reseeded.	Drought	Significant alterations to the topography had to be made to restore the natural hydrology.

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Wild Mile Restoration Project	Chicago, IL	City of Chicago, Urban Rivers	Dechannelization, revegetation, installing aeration waterfalls, removing armored shoreline defenses	17 acres	1.4 million	Ongoing	In an industrial section of Chicago, workers are restoring riparian areas along the Chicago River by removing armored shoreline defenses and replacing them with native riparian vegetation. Aeration waterfalls will help increase dissolved oxygen levels for fish.	Inland flooding	Creating a gradual transition from land to water in the riparian zone is a challenge in an urban environment.
Dolores River Restoration Partnership	Eastern Utah and western Colorado	**Bureau of Land Management,** The Nature Conservancy, The Walton Family Foundation	Invasive species removal using biocontrol, chemical treatment and mechanical control; planting native vegetation	1,140 acres	1.26 million	6 years	Invasive species were removed along the banks of the Dolores River using a plethora of different methods. Native flora were then planted	Drought	A variety of invasive species treatment was found to be most effective when used in combination

Bolding indicates DOI affiliates.

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Riverine Habitats
24. Riverine Connectivity Restoration

DEFINITION

A *riverine system* is a watershed-scale network of integrated aquatic habitats and hydrological processes (McCluney et al. 2014). A riverine system consists of the area drained by a primary river and its tributaries. A riverine system functions as both a habitat and migration corridor, with connectivity projects enhancing the sustainability of both (Seliger and Zeiringer 2018). Riverine connectivity is concerned with providing longitudinal access between points along the main channel of a river. A well-connected river sustains natural riverine processes, including the unimpeded movement of fish, sediment, and nutrients to points further up- and downstream (MDBA n.d.). This reduces habitat fragmentation, flow alterations, and conditions conducive to invasive species (Arboleya et al. 2021). Riverine connectivity is blocked by numerous anthropogenic alterations to rivers, including weirs, dams, culverts, fords, sluice gates, and roads (Soton 2018). Restoring riverine connectivity as a nature-based solution (NBS) involves removing these physical barriers, eliminating hypoxic zones, redesigning road stream crossings, and reintroducing natural meanders back into river morphology (Woolsey et al. 2007).

TECHNICAL APPROACH

The following strategies are frequently used to restore riverine connectivity:

- **Dam removal:** Dams alter nutrient cycling, impact the deposition of sediment, reduce flood frequency, and limit the range of migratory aquatic species, all of which deprive rivers of their ecological health (Bednarek 2001). Once a dam is removed (Figure 1), river flow will increase, decreasing temperature and increasing dissolved oxygen levels (Higgs 2002). While these changes may have a short-term negative impact on the ecosystem as a result of the large flux in conditions immediately afterward, they are far outweighed by the long-term benefits. Fish migration, sediment deposition, and a decrease in eutrophication help nurture the river back to its natural state (Higgs 2002). Dam removal techniques vary. Often, water is diverted so that the dam can be deconstructed "in the dry." Alternatively, dams can be deconstructed "in the wet," where the dam is slowly lowered over an extended duration of time to allow the riverine system time to adjust to the new water flow (American Rivers 2023).
- **Invasive species removal:** Invasive species can have profound impacts on the hydrology of a riverine system. Invasive species generally use more water than native ones, reducing river flow and exacerbating drought (Jansson et al. 2007). Frequent invasive species in American rivers include zebra mussels (*Dreissena polymorpha*), lampreys (*Petromyzontiformes spp.*), purple loosestrife (*Lythrum salicaria*) and nutrias (*Myocastor coypus*). While control methods vary depending on the target species, common strategies involve biological, chemical, mechanical, physical, and cultural approaches (USDA 2023).

Figure 24.1 Dam removal on Octoraro Creek, MD

Photo courtesy US Fish and Wildlife Service

- **Replacing culverts:** Culverts block migration of fish and aquatic species when they are too small, steep, or at a higher elevation than the water directly downstream (NOAA 2022). Existing culverts can be replaced with larger, less-steep ones to address these issues (Figure 2). Culverts must be large enough to transport fish and sediments downriver while still accommodating the existing road infrastructure passing over the stream (Wellman et al. 2000).
- **Redesigning road stream crossings:** Like culverts, many road stream crossings are poorly designed and hinder the movement of wildlife throughout the length of a river or creek. Poorly designed road stream crossings include vertical barriers, low-water crossings, unnatural bed substrates, high–water velocity crossings, clogged crossings, and crossings that cause bed scour. These can be replaced with well-designed crossings that better account for local geomorphology. Characteristics of well-designed crossings include comparable water depth and flow to nearby stream conditions, sufficient size for high flows, retaining the natural stream channel and substrates and spanning the entire stream (Gring 2021).
- **Eliminating hypoxic zones:** *Hypoxia* refers to low levels of dissolved oxygen in aquatic habitats, making hypoxic zones virtually devoid of aquatic life (NOAA 2023). Hypoxic zones often occur in river deltas or near the mouths of major rivers because nutrient pollution (primarily nitrogen and phosphorus) from the whole riverine system

Figure 24.2 Fish-friendly culvert in Anchorage, AK

Photo courtesy US Fish and Wildlife Service Alaska Region

accumulates here (Mitsch and Day 2006). This blocks aquatic organisms from entering and exiting the riverine system (NOAA 2023). Numerous strategies can be used to mitigate nutrient pollution and thus reduce hypoxic zones. These include planting wetlands near agricultural areas, installing riparian buffers, and changing agricultural practices (Mitsch and Day 2006).

- **Reintroducing natural meanders:** *Meanders*, where the main channel of a river migrates through its floodplain in a curved shape, are frequently straightened to make rivers more navigable for large ships (NWRM 2013). However, this reduces the diversity of habitats within a river and makes portions of the river unnavigable for some species (Pess et al. 2006). Heavy equipment can be used to change the local topography and reconnect the main channel with cut-off meanders in the floodplain, reducing the water velocity of the river (NWRM 2013).
- **Fish passage structures:** In cases where removing dams or weirs is not possible, fish passage structures can still enhance riverine connectivity for migratory fish (Figure 3). Examples of fish passage structures include bypass channels, fish locks, fish ladders, and fish lifts (Beechie and Roni 2012). Many of the designs combine green and grey infrastructure and are placed adjacent to a dam or weir (Beechie and Roni 2012).

OPERATIONS AND MAINTENANCE

Operations and maintenance will differ for various riverine connectivity project types, but these activities can include intermittent invasive species removal efforts, removing blockages from culverts and stream crossing structures, and maintaining fish passage structures as they age.

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Dams that are no longer in use:** Dams that are no longer functioning for their original purpose are often targeted for removal. Since the dam is no longer generating revenue, maintenance costs begin to pile up. Often, dams are removed when removal is deemed cheaper than maintenance (American Rivers 2023).
- ✓ **Ample space between infrastructure and the river:** Having a buffer zone to allow for changes in the hydrological regime of the river is ideal. Having extra room along the riverbank allows for the incorporation of natural meanders and diverse aquatic habitats into a project.

Figure 24.3 Fish ladder in Vermont

Photo courtesy US Fish and Wildlife Service Northeast Region

- ✓ **Near a restored wetlands or floodplains site:** Pairing wetland restoration or floodplain reconnection with a riverine connectivity allows benefits from the adjacent ecosystem to help the project. For example, building side channels for salmon spawning grounds as a part of a floodplain reconnection project multiplies the benefits of building a fish passage structure in a riverine connectivity project.
- ✓ **Near the mouth of the river:** Removing barriers to riverine connectivity near the outlet of a river will have a greater impact on all upstream tributaries.
- ✓ **Overpasses for smaller rural roads and trails:** Despite receiving little traffic, rural road and trail overpasses pose significant barriers to riverine connectivity. These overpasses are generally small, meaning that renovating or replacing them will be less expensive (Gring 2021). Many of these routes are seldom-traveled, resulting in minimal economic disruptions while realizing large benefits for wildlife.
- ✗ **Areas prone to erosion:** Riverbed erosion deprives the area of sediment needed sustain a healthy river. Unless the source of erosion is being addressed as a part of the project, then eroded areas should be avoided (Rhode et al. 2006).
- ✗ **Densely populated urban areas:** The lack of open space and highly modified nature of urban rivers makes it difficult to implement river restoration in urban areas. However, urban rivers can still use riverine connectivity techniques as a part of a green-gray approach (Guimarães et al. 2021).
- ✗ **Flood-prone regions:** Removing gray infrastructure may increase flood risk in areas with high amounts of development in the floodplain. For example, dam and levee removal as a part of riverine connectivity can result in flooding downstream (Guimarães et al. 2021).
- ✗ **Areas with frequent commercial shipping:** Locks, which pose a major barrier to riverine connectivity, are vital for commercial ships traversing rivers with steep gradients. Furthermore, vessel-induced waves from large ships can cause habitat loss and riverbank erosion (Liedermann et al. 2014). Thus, rivers that receive heavy commercial ship travel are generally not suitable for a riverine connectivity project.

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?
Stream and Watershed Restoration: A Guide to Restoring Riverine Processes and Habitats	Guidebook	2012	Philip Roni and Tim Beechie	National	This comprehensive resource provides in-depth information for developing watershed restoration projects. Topics covered include the human dimensions of riverine connectivity, identifying restoration needs, developing and implementing projects, and project monitoring and evaluation.	✓	✓	✓	—
Renewing Our Rivers: Stream Corridor Restoration in Dryland Regions	Guidebook	2021	Mark K. Briggs and Waite R. Osterkamp	Focus on arid regions but most of the information is more broadly applicable	With a special emphasis on the role climate change plays in shaping riverine systems, this resource provides information on how to plan and enact a river restoration project. With numerous case studies of successful riverine connectivity projects, the guidebook provides insights into designing an effective plan.	✓	✓	✓	✓
Iowa's River Restoration Toolbox	Website	Not provided	Iowa Department of Natural Resources	Focus on Iowa but most of the information is more broadly applicable	Comprised of numerous detailed diagrams, this tool provides technical information for assessing a waterbody and determining the appropriate restoration technique. In depth information is also given about contractor relations and project execution.	✓	✓	—	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
National River Restoration Scientific Synthesis (NRRSS) Database	Database	2007	American Rivers, University of Michigan, University of Maryland	National	Compiled by scientists, the NRRSS database contains information about more than 37,000 river restoration projects in the United States It also collects scientific papers on river connectivity that originated from information found in the database.	✓	—	—	✓
Society for Ecological Restoration (SER) Project Database	Database	2023	Society for Ecological Restoration	Global	Comprised of projects from around the world, the SER database is a vast repository of ecological knowledge. To find projects specifically related to riverine connectivity, filters can narrow down results by ecosystem and biome type.	—	—	—	✓
River Restoration Science & Socio-Economic Resources	Website	2023	American Rivers	National	The website provides a diversity of tools highlighting the best practices for riverine connectivity restoration. A special emphasis is placed on dam removal, floodplain restoration, and the economics of river restoration.	✓	✓	✓	✓
River Barrier Prioritizations Database	Website	2023	American Rivers	National	This is an inventory of barriers to aquatic connectivity in the United States. The database also prioritizes structures whose removal would be particularly ecologically beneficial.	—	✓	—	✓

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Low-Tech Process-Based Restoration of Riverscapes Design Manual	Guidebook	2019	Utah State University Restoration Consortium	National	The authors show how river restoration centers around restoring the hydrological processes that make a riverine system successful. The guide focuses on low-tech and cost-efficient solutions, including beaver dam analogs and assisted wood accumulation.	✓	—	✓	✓
USA Dam Removal Experience and Planning	Guidebook	2021	US Bureau of Reclamation	National	This document compiles knowledge about dam removal design, planning, and monitoring. This resource also provides case studies of successful dam removal projects and their associated ecological benefits.	✓	✓	✓	✓

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Reduced flooding:** Well-connected rivers can adequately distribute excess water throughout the riverine network during peak flow times, given a functioning floodplain (see floodplain reconnection strategy) (Trigg et al. 2013).
- **Drought mitigation:** Rivers are better able to respond to droughts when they are connected. During droughts, rivers may temporarily dry up in certain locations, so connectivity allows aquatic animals to move along the length of a river to interbreed with other populations (Palmer and Ruhi 2019). Additionally, riverine connectivity increases the frequency of the river flow and enhances the hydrological exchange with

the hyporheic zone, where river water percolates into groundwater aquifers, thus better recharging aquifers that can sustain communities through droughts (Song et al. 2018).

- **Sea level rise adaptation and resilience:** Connected rivers deliver sediment to the mouth of the river, helping the area around the river delta keep pace with sea level rise (Phillips and Slattery 2006). However, natural sediment deposition has been disrupted by anthropogenic alterations to rivers, especially dams, which trap sediment upstream (Topping et al. 2000). Restoring riverine connectivity by removing dams and other barriers allows sediment deposition to resume (Bednarek 2001).
- **Carbon storage and sequestration:** River channels can store more carbon per acre than upland ecosystems because of the large amount of soil organic carbon and downed wood (Wohl 2020).

Social and Economic

- **Increased property values:** Property values in areas near a restored river have been found to significantly increase following dam removal (Lewis et al. 2008).
- **Recreational opportunities:** Riverine connectivity provides an opportunity for additional parkland along the river, boosting tourism and recreation opportunities.
- **Clean drinking water:** Riverine connectivity enhances the natural purification qualities of a river, resulting in cleaner drinking water and less anthropogenic drinking water treatment (Chen et al. 2022).
- **Jobs:** Workers will need to be hired to perform the riverine connectivity projects, boosting the local economy.
- **Mental health and well-being:** Restored rivers can serve as greenspace, which strengthens residents' mental health.
- **Resilient fisheries:** Restoring local fisheries is one of the most common objectives cited by entities completing riverine connectivity projects. Riverine connectivity allows migrating species to return to their spawning grounds and increases genetic diversity within populations (Beechie et al. 2008). There are many varieties of fish passage structures that aid fish's longitudinal connectivity throughout a river basin (Beechie and Roni 2012).
- **Cultural values:** Riverine connectivity can increase local awareness of and pride in aquatic ecosystems. Aquatic species and ecosystem processes restored via riverine connectivity are integral to traditions of many Indigenous communities.

Ecological

- **Improved water quality:** Disruption to river flow hinders natural riverine processes that purify water. Connected rivers foster healthier ecosystems that are better able to tolerate and neutralize pollutants (Zaidel et al. 2021). By reducing erosion and other sources of excess sediments, riverine connectivity also reduces turbidity and increases water clarity (Palmer et al. 2005).

- **Enhanced biodiversity:** Enhanced riverine connectivity has been shown to increase both species richness and species diversity. This can be attributed to greater organism movement, less pollutants and eutrophication, and higher dissolved oxygen levels in well-connected rivers (Cantonati et al. 2020).
- **Enhanced genetic diversity:** Dams create isolated populations of fish who can only interbreed among themselves, reducing the gene pool. Once a river is reconnected, isolated fish populations can intermix, resulting in a fresh infusion of genes and increasing the health of the population (Piotrowski 2021).
- **Supports wildlife:** Riverine connectivity can allow for more exchanges with the surrounding floodplain (lateral connectivity) (see floodplain reconnection strategy) and a greater diversity of habitats surrounding the riverine ecosystem, from the groundwater to the atmosphere (vertical connectivity) (MN DNR 2023).
- **Increased primary productivity:** Riverine ecosystems thrive on variable water flows, which are stabilized by blockages in the river such as dams. Restoring flow variability eliminates numerous competitively dominant species, enhancing the whole ecosystem and increasing primary productivity (Palmer et al. 2005).

BARRIERS AND SOLUTIONS FOR PRACTITIONERS

Common Barriers

Several barriers are common across many of the NBS strategies; these are described in more detail in the Section 1 of the Roadmap. Additional notes about the barriers specific to riverine connectivity are included here.

- **Expense:** Because of the large scale of infrastructure blocking rivers, costs to restore riverine connectivity are high. The Elwha Dam removal project, one of the largest in the United States, cost $325 million (Cho 2011). Even smaller removals can still be pricey. The removal of a small dam system that once powered textile mills along the Patapsco River in Maryland cost $2.7 million (Hirsch 2012).
- **Capacity**
- **Public opinion**
- **Conflict with other land uses:** There are currently 2,210 hydroelectric dams in the United States, producing 6.3% of the nation's electricity (Cho 2011, DOE 2023). Reliance on hydropower is even more pronounced in some areas of the country. The Bonneville Power Administration, which only produces electricity via hydropower, provides 28% of the Pacific Northwest's electricity (BPA 2023). Dam removal also significantly reduces the amount of water available in reservoirs, although free-flowing rivers are more effective at storing water in underground aquifers (Poff and Hart 2002). Thus, it is not economically viable to remove dams in many instances.
- **Regulation**
- **Lack of effectiveness data**

Economic

- **Impact on agricultural practices:** Given that remediating hypoxic zones is a way to improve riverine connectivity, this solution is reliant on farmers reducing their nutrient pollution (Mitsch and Day 2006). Transitioning to more sustainable practices to reduce nutrient runoff may economically hurt some agricultural facilities (EPA 2022).

Community

- **Change in local flood regime:** Flood-control dams are built to alter the seasonal flow patterns of rivers, reducing peak flows and mitigating floods. When the dam is removed the natural flood regime will gradually reemerge, resulting in more frequent floods (Poff and Hart 2002). Downstream development previously protected by the dam will now become flood-prone.
- **Jurisdictional overlaps:** Rivers are common physical boundaries that divide political entities. As a result, opposite banks of a river are often subject to different jurisdictional authorities. This makes it difficult to coordinate riverine connectivity projects.

Ecological

- **Managing sediment built up behind dams:** While dam removal helps sediment transportation in the long term, in the short term, dam removal can stir up excess sediments and transport them downriver. These sediments are often laden with toxic chemicals, greatly damaging downriver habitat (Cho 2011).
- **Rapid shifts in biogeochemical cycling:** Similar to sediment transport, removing river barriers temporarily disrupts biogeochemical cycling while restoring it in the long term. Large quantities of nitrogen and phosphorus that accumulated behind barriers are suddenly released, creating a surplus of nitrogen and phosphorus downriver (Hart et al. 2002).
- **Invasive species proliferation:** Many nascent aquatic invasive species have their range limited by artificial river barriers (Habel et al. 2020). However, once these barriers are removed, the invasive species can travel to previously protected habitats, outcompeting native species.

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Potomac Headwaters Fish Passage Restoration Project	Potomac headwaters of the Chesapeake Bay (Maryland, Virginia, West Virginia)	**US Fish and Wildlife Service (USFWS)**	Culvert replacement, redesigned road stream crossings, fish passage structures	195 stream miles reconnected	1.15 million	Ongoing, began 2022	The project is removing 17 barriers to fish passage along the tributaries of the Potomac River. This includes culvert and low bridge replacements, dam removal, and installing fish ladders.	Inland flooding	No
Sabattus River Connectivity Project	Lisbon, Maine	**USFWS,** Maine Department of Natural Resources, Town of Lisbon, Atlantic Salmon Federation	Dam removal	9 river miles reconnected	650,000	3	Contractors removed two failed dams that blocked fish passage and posed a flood risk to the town of Lisbon.	Inland flooding	Removing the dams allowed for the Sabattus River to better manage stormwater runoff.
Good River Connectivity Project	Gustavus, Alaska	**USFWS,** Alaska Department of Natural Resources, City of Gustavus, National Oceanic and Atmospheric Administration (NOAA), National Wildlife Federation	Culvert replacement, redesigning road stream crossing	6 stream miles reconnected	1.76 million	5	To restore river connectivity, culvert crossings on the Good River were replaced with bridges that allowed fish to pass.	No	Isostatic rebound, where land rises after an ice sheet retreats, caused an imbalance in elevation that blocked fish from passing.
Upper Clark Fork Fish Passage Project	Upper Clark Fork River, Montana	**USFWS,** US Department of Agriculture Forest Service, Montana Department of Natural Resources, Trout Unlimited	Dam removal, fish passage structures	55 river miles reconnected	250,000	1	The team used a plethora of fish passage structures to help fish navigate barriers on the Upper Clark Fork River.	No	Because many of the structures removed were historic, the permitting process took extra time and drive.

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Moose Creek Connectivity Project	Moose Creek, Alaska	**National Park Service (NPS), USFWS,** NOAA, Chickaloon Native Village	Reintroducing natural meanders, weir removal, logjam installation	5 creek miles reconnected	Not provided	2	Managers removed weirs, reintroduced natural meanders to slow water flow, and installed logjams to help restore the natural hydrology of Moose Creek.	No	The team used historical railroad maps to discover the natural flow of the creek before it was altered.
Bluebird Dam Removal Project	Rocky Mountain National Park, Colorado	**NPS, Reclamation,** US Army Corps of Engineers (USACE)	Dam removal, vegetation planted	17 acres	1.3 million	2	After the catastrophic failure of another dam in Rocky Mountain National Park, the Bluebird Dam was inspected and found to be structurally unsound. The dam was removed and native vegetation was replanted in the former reservoir.	Inland flooding	To avoid adverse impacts to the native flora and fauna, multiple helicopters were used to transport rubble away from the site.
Carmel River Restoration Project	Carmel River, California	**Bureau of Land Management (BLM), USFWS,** NOAA, USACE, California State Coastal Conservancy	Dam removal, revegetation, boulder installation, off channel creation	25 river miles reconnected	84 million	3	After sediment buildup, nutrient pollution, and flooding caused by the San Clemente Dam degraded the Carmel River, officials decided to remove this large dam.	Inland flooding	Because of the severe sediment buildup behind the dam, engineers decided to reroute the river and plug the sediment before deconstructing the dam.

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Neuse River Restoration Project	Neuse River, North Carolina	**USFWS,** US Environmental Protection Agency, NC Department of Environment and Natural Resources, USACE, NC Coastal Federation	Dam removal	1,000 miles of river and tributaries reopened	Not provided	20	Beginning 1997 and ending in 2017, six dams along the Neuse River were removed. While most dams were built to produce hydropower, drought and flood risk made upkeep impractical.	Inland flooding	By viewing river connectivity at the large scale of the total Neuse River Basin, each successive dam removal project was able to amplify the benefits of the previous one.

Bolding indicates DOI affiliates.

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Riverine Habitats
25. Stream Restoration

DEFINITION

A *stream*, also known as a *branch*, *creek*, *run*, or *brook*, is a continuous surface flow of freshwater within a channel that is smaller than a river. Headwater streams can originate from groundwater (springs), runoff, or a wetland. Streams and rivers flow more than 3.5 million miles across the United States and are present in every region (EPA 2013). Streams are generally too small to have their own floodplain and run at steeper gradients and faster velocities than rivers, resulting in a greater amount of dissolved oxygen (USGS 2018). Nationally, stream health is declining as a result of an increase in impervious surfaces, polluted stormwater runoff, nutrient pollution, drought, deforestation, and physical barriers. As a response to this decline, communities are working to restore streams, with more than $1 billion a year spent on stream and river restoration in the United States (Bernhardt et al. 2005). Stream restoration techniques fall into two categories: form-based (which is more common) and process-based (Roni et al. 2002). Common techniques include brush layering, coir log installations, cross vanes, grading stream banks, log vanes, J-hooks, and step pools (MCDEP 2023).

TECHNICAL APPROACH

Form-based restoration involves physically manipulating the components of a stream to restore it to its natural morphology. This approach has many benefits, including enhancing fish habitat, reducing erosion, controlling water flow, and improving water quality. On the other hand, process-based restoration focuses on restoring the ecological interactions that occur in the stream, primarily by balancing biogeochemical cycles and enhancing organism movement. Given that stream ecology is heavily influenced by surrounding land uses, the scope of process-based restoration often reaches beyond the banks of the stream (Wohl et al. 2015).

Form-Based Restoration

- **Brush layering:** *Brush layering* involves taking small pieces of live cuttings from native plants and placing them at the bottom of a small terrace along the stream. The top of the cuttings should barely protrude from the ground, catching runoff and sediments. Eventually, live cuttings will begin to regenerate, growing roots and leaves and creating a living mat to protect the stream (Bischetti et al. 2010).
- **Coir logs:** A *coir log*, a type of geotextile, is a mesh netting made of coconut fibers that helps reduce erosion. Used in other nature-based solutions such as living shorelines (see summary), coir logs are biodegradable while holding soil in place and promoting plant growth. Coir logs are placed at the base of steep stream banks to keep them from eroding (Unser et al. 2009).

- **Cross vanes:** Building a cross vane involves placing a group of stones in a U shape across the width of the stream. The bottom of the U should be facing upstream. This directs the water toward the center of the stream, reducing erosion from water lapping up against the banks. Cross vanes also establish grade control by creating a slight elevation difference between the upstream and downstream portions of the structure (Gordon et al. 2013).
- **Regrading stream banks:** Steep slopes increase the amount of runoff that enters a stream, increasing the amount of water-borne pollutants and likelihood of flooding. Regrading steam banks entails terracing the banks into a series of small, gently sloping banks. Native vegetation can then be replanted to increase water retention (Figure 1). This results in reduced erosion and higher levels of groundwater recharge (Bernhardt and Palmer 2007).
- **Beaver management and beaver dam analogs (BDAs):** Beaver engineering profoundly reshapes the morphology of streams, creating wetlands and a diverse array of channel sizes. Maintaining a population of beavers enhances stream health, even in urban areas (Bailey et al. 2019). In areas where no beavers are present, building a BDA can replicate many of the same benefits of natural beaver dams. For more information on beavers, please see the beaver management and BDA summary.

Figure 25.1 A regraded and planted stream bank at Raccoon Creek, GA

Photo courtesy US Fish and Wildlife Service Southeast Region

- **J-hooks:** *J-hooks* are similar to cross vanes, but only span half of the stream. A J-hook has holes in between its rocks, allowing fast-flowing water to move through and creating a pool of stagnant water for aquatic organisms to live in. Reduced erosion and stream water velocity are additional J-hook benefits (Toran et al. 2012).
- **Log vanes:** In a log vane, large logs are placed across the stream, directing water flow away from an eroding bank. This results in the formation of scour flows directly below the log, providing habitat for aquatic organisms (MCDEP 2023).
- **Rock pack:** In streams that experience large runoff flows, trees along the bank of the stream can often be destabilized. Large stones can be placed around the base and roots of the tree to prevent it from falling into the stream (NRCS 2012).
- **Root wads:** A *root wad* refers to the tangle of roots that is often exposed in a downed tree, accompanied by the tree's stump. Root wads can be placed along a stream bank to protect the bank and provide habitat (Doll et al. 2003).
- **Step pools:** *Step pools* are a staircase-like configuration of rocks that slow down the stream flow over steep gradients. It is important to ensure that individual steps are not too high (above 30 cm), as this will promote undercutting and block fish passage (Purcell et al. 2002).
- **Stone toe protection:** Similar to other bank protection strategies, stone toe protection reduces the amount of runoff that enters the stream. A row of large stones is placed at the bank of the stream, protecting the bank from erosion and helping to reform the bank into a gentler slope (Shields et al. 1998).
- **Woody debris:** *Woody debris*, which encompasses large wood deposits and engineered log jams, serves the purpose of redirecting stream water into braided channels, slowing stream flow and providing fish habitat. Woody debris structure designs vary widely, but generally involve anchoring pieces of wood to a stream bank (Abbe et al. 2018).

Process-Based Restoration

- **Removing anthropogenic barriers in streams:** There are more than 2 million barriers to rivers and streams across the United States, inhibiting the flow of fish, nutrients, sediment, and water. This severely alters the processes that drive the stream and affect temperature and dissolved oxygen levels (Higgs 2002). Stream barriers, including small dams, weirs, culverts, and sluice gates, can be removed to restore the ecological benefits of the stream. This process is becoming increasingly common, with 65 dams being removed in the United States in 2023 alone (Thomas-Blate 2023). For technical guidance on the process of stream barrier removal, please see the riverine connectivity restoration summary.
- **Delineating a stream migration corridor:** Streams naturally migrate over time as their channel morphology changes. However, this migration is frequently blocked by infrastructure close to the stream. Proactively purchasing and maintaining natural lands around streams helps sustain the migration process, as well as reducing flood risk for surrounding structures. This gives streams the space to heal themselves, facilitating natural changes to stream morphology (Biron et al. 2014).

- **Reducing nutrient pollution:** Limiting the amount of nutrient pollution that enters a stream is a critical component of restoring stream health. This primarily done by planting riparian buffers, which are highly effective at capturing nutrient pollution (Vietz et al. 2016). For more detailed information on planting riparian buffers, please see the riparian buffer restoration summary.

These techniques can be implemented alone or in tandem with other approaches. One activity that cross-cuts many stream restoration projects is replanting native species. Native plants are used to reduce erosion on steep slopes and restore aquatic habitats within streams. A variety of planting techniques are used, including live cuttings, seeds, and planting plugs (Selvakumar et al. 2010).

Like many aquatic ecosystems, streams are prone to being overrun by invasive species. Streams are especially susceptible to invasive species because they are often located in urban environments, which enable conditions that favor these species. Invasive species can be removed either before or after the primary restoration activities, with many managers waiting until after the project to see if the new stream conditions will naturally eradicate the invasives. Common invasive species in streams include purple loosestrife (*Lythrum salicaria*), water thyme (*Hydrilla*), and goldfish (*Carassius auratus*) (Sulpizio 2020).

OPERATIONS AND MAINTENANCE

Stream restoration projects require regular trash and debris removal, especially after flood events. Invasive species management may also be required. Woody debris will likely need to be replaced every other year. Some restoration sites experience erosion issues and may need to be replanted.

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Low gradients:** While many streams naturally flow at high gradients, stream restoration projects generally focus on low-gradient streams because they are less risky. The morphology of low gradients can be more easily manipulated without risking catastrophic erosion (Miller and Kochel 2010).
- ✓ **Cohesive banks:** *Cohesive banks* refers to stream banks with high quantities of clay or silt sediments. Restoration projects with cohesive banks have had greater success rates in the past because of their compatibility with in-stream structures such as cross vanes (Miller and Kochel 2010).
- ✓ **Bank erosion:** Bank erosion is one of the primary processes that stream restoration is attempting to reverse. Siting a project in an area with bank erosion will help magnify the benefits by preventing excess sediment from entering the stream. However, it is important to determine the source of bank erosion before starting the project, as a poorly designed restoration project can exacerbate the problem (NRCS 2007).
- ✓ **Near sources of nutrient pollution:** Nutrient pollution enters a watershed primarily through small streams. Restoring first- to third-order streams near sources of nutrient pollution such as agricultural fields maximizes the amount of nutrient pollution averted. Furthermore, smaller streams are generally simpler to restore, with less resources needed to build in-stream structures (Craig et al. 2008).

- ✓ **Large amounts of impervious surfaces:** Impervious surfaces block precipitation from percolating into the ground, increasing the amount of runoff that a stream must handle. Strengthening the ecological resiliency of the stream via restoration will allow it to better handle these increased flows (Sweeney et. Al. 2013).
- ✗ **Downstream of large sediment supplies:** While a stable sediment supply is necessary to prevent erosion of the stream, excess sediment causes problems by changing channel form. Recent housing developments, landslides, and eroded banks with little vegetation further upstream will impact the restoration site with excess sediment (Miller and Kochel 2010).
- ✗ **High stream power:** High stream power exacerbates current erosion problems, making them more difficult to remediate. This also makes it more difficult to build in-stream structures and direct water to the appropriate places (Miller and Kochel 2010).
- ✗ **Stream barriers that will not be removed as a part of the project:** Stream barriers will inhibit water flow and the transport of nutrients and sediment, preventing the stream from functioning in its natural state. If a stream barrier is located near the project site, then it is not worth investing the resources in restoration only to see the benefits masked (Rinaldi and Johnson 1997).
- ✗ **Streams running through wetlands:** Wetlands alter the flow regime of streams by slowing down and dispersing the water. The techniques mentioned in this summary were not designed for this environment. For more information on restoring inland wetlands, please see the inland wetlands summary.
- ✗ **Poor access:** Access to many smaller, forested streams can be difficult, often resulting in the felling of trees to make room for heavy machinery to reach the restoration site. In these scenarios, the environmental impacts of restoration often outweigh the benefits, making these sites poor choices for restoration.

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?
Stream Restoration: A Natural Channel Design Guidebook	Guidebook	2003	NC State University, NC A&T University, North Carolina Sea Grant	National	This guide covers siting, designing, and monitoring stream restoration projects to maximize ecological benefits. Additional topics covered include installing riparian buffers, flood studies, and an introduction to fluvial processes.	✓	✓	✓	—
Stream Restoration Design Field Guide	Guidebook	2008	US Department of Agriculture Natural Resources Conservation Service (NRCS)	National	Filled with diagrams illustrating specific stream restoration techniques, this guide provides helpful design ideas. The designs cover numerous strategies, including determining rock size, bank stabilization, and redirecting water flow.	✓	—	—	—
Large Wood Design Guidelines—National Manual	Guidebook	2016	US Army Corps of Engineers and **US Bureau of Reclamation (USBR)**	National	Encompassing all aspects of large wood designs, this guide covers their geomorphic, hydrological, and ecological considerations. The authors also discuss the risks involved, regulatory considerations, and monitoring.	✓	✓	✓	—
Stream Restoration Design	Guidebook	2007	NRCS	National	Written by a distinguished team of stream experts, this guide covers different stream design processes and channel configurations. Additional topics covered include permitting, stream hydrology, and impacts on sediment.	✓	✓	✓	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
A Handbook for Prioritizing Wetland and Stream Restoration and Protection Using Landscape Analysis Tools	Guidebook	2013	Environmental Law Institute	National	Focusing on site selection, this guide helps managers use landscape analysis tools to determine the best sites for stream restoration based on social, environmental, and economic metrics. The authors also discuss the regulatory hurdles involved in stream restoration as well as non-regulatory markets for ecosystem services.	—	✓	✓	—
Restoring Western Headwater Streams with Low-Tech Process-Based Methods	Guidebook	2013	American Rivers	Western United States	This guide explains the difference between low-tech process-based restoration and traditional stream restoration methods, describing lessons learned from past projects. The authors include case studies, benefits, and funding sources.	✓	—	✓	✓
Rock Weir Design Guidance	Guidebook	2016	USBR	National	Rock weirs encompass multiple stream restoration techniques, including J-hooks, cross vanes, and step pools. The authors provide design guidance and information about the hydrology and geomorphology of rock weirs.	✓	—	✓	—
Rock Ramp Design Guidelines	Guidebook	2007	USBR	Western United States	Rock ramps include numerous bank protection techniques such as rock pack and stone toe protection. The authors discuss issues related to fish passage, constructed step pools, and riprap sizing.	✓	✓	—	✓

GRAY INFRASTRUCTURE ALTERNATIVES

Stream restoration can be an alternative to gray infrastructure approaches that address riverine flooding (levee and dike systems) or urban runoff (stormwater drainage systems). The ability of a stream restoration project to replace or supplement these gray infrastructure approaches 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 stream restoration. See the gray infrastructure alternative tables in Section 1 for a comparison of stream restoration to these alternatives.

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Reduced flooding:** Stream restoration attenuates floods by dissipating water energy by reintroducing natural meanders back into the stream. Reductions in channel slope and increases in channel length allow for a stream to temporarily hold more water, preventing excess water from flooding surrounding areas. Restored banks are also better able to divert runoff into the ground, limiting the amount of water the stream must handle (Sholtes 2009).
- **Drought mitigation:** Stream restoration spreads out the peak flows of a stream, keeping water in the riverine system over a longer period of time. Restoration also increases connectivity between streams and wetlands, which store excess water that can be accessed during times of drought. Finally, restoration can facilitate groundwater recharge both in riparian areas and the hyporheic zone of the steam, preparing a region for drought (Ameli and Creed 2019).
- **Reduced wildfire risk:** Stream restoration promotes healthy and adequately hydrated vegetation around the stream, increasing fire resistance. Furthermore, restored streams keep the ground around the stream more moist than degraded streams, limiting fire spread. Certain stream restoration techniques, such as BDAs, create wetlands that can serve as a large firebreak (Pugh et al. 2022).
- **Carbon storage and sequestration:** While the amount of carbon sequestered because of stream restoration varies based on the geographic setting, a restored stream stores significantly more carbon than a degraded one. Increased riparian vegetation, large wood, and soil carbon are all carbon sinks enhanced by stream restoration. Stream restoration holds water for longer periods within the riverine system, promoting plant growth and higher carbon concentrations in the soil (Hinshaw and Wohl 2021).
- **Heat mitigation:** Stream restoration promotes the growth of riparian vegetation, which reduces air temperatures in the surrounding areas. Additionally, a vegetated canopy shields the water from the sun, reducing water temperature and thus mortality in aquatic species. This benefit is especially pronounced in urban streams, where heavily vegetated streams play a major role in mitigating the urban heat island effect (Abdi et al. 2020).

Social and Economic

- **Recreational opportunities:** Stream restoration makes streams a much more visual pleasing and safe site to visit, increasing recreational activities along the stream. Stream restoration paves the way for recreational activities such as hiking, birdwatching, and canoeing (Kondolf and Micheli 1995).
- **Reduced erosion:** Stream restoration diverts water away from eroding banks and toward the middle of the channel, reducing erosion. Stabilizing materials such as coir logs, stone-toe protection, and woody debris slow runoff as it descends the streambank, limiting erosion. Vegetation growth promoted by planting native species and live cuttings alters the local microclimate, resulting in conditions that support soil stability (Wynn, Mostaghimi and Alphin 2004).
- **Clean drinking water:** Stream restoration filters harmful pollutants and excess nutrients out of the stream, preventing it from entering larger rivers. Furthermore, when stream temperatures rise, water filtration plants often must apply additional treatment measures to the water, increasing the cost. However, since stream restoration lowers the water temperature, healthy streams can reduce water treatment expenses (Honey-Rosés et al. 2013).
- **Jobs:** Contractors will need to be hired to perform the restoration activities, stimulating the local economy.
- **Mental health and well-being:** Stream restoration enhances greenspace, boosting residents' mental health and psychological well-being.
- **Resilient fisheries:** Stream restoration increases both water quality and quantity, improving conditions for fish. More complex stream morphology allows for greater habitat diversity, providing nursery grounds for juvenile fish. Additionally, removing stream barriers facilitates fish passage, enhancing the longitudinal connectivity of the stream (Shirey et al. 2016).
- **Cultural values:** Streams and their inhabitants are important in a variety of cultures. Stream restoration can also be an opportunity to educate the public about the value role streams play in protecting water quality.

Ecological

- **Improved water quality:** Stream restoration improves water quality by lowering the amount of excess nutrients and sediments entering a stream. Streams are ecologically sensitive, meaning they cannot tolerate large fluxes of nutrients or sediments. Bank stabilization techniques guard the stream from nutrient and sediment runoff and in-stream rock structures limit channel erosion, improving water quality (Thompson et al. 2018). Stream restoration increases connectivity between the stream and its floodplain. Floodplain and riparian vegetation can trap excess nutrients, preventing them from flowing downstream. Furthermore, bank revegetation can prevent nutrients from entering the stream to begin with, as riparian vegetation is able to absorb excess nutrients (McMillan and Noe 2017). Stream restoration also reduces erosion, lowering the amount of sediment that enters a stream. This results in a lower concentration of suspended sediments in the stream, reducing the turbidity of the water and enhancing water quality (Siemion et al. 2016).

- **Enhanced biodiversity:** While stream restoration can increase biodiversity, increasing habitat diversity alone is not enough to restore biodiversity. Removing anthropogenic barriers in streams, limiting water extractions, reducing agricultural runoff, and removing invasive species are effective restoration strategies that can further increase biodiversity (Palmer et al. 2010).
- **Reduced runoff:** One of the primary goals of stream restoration is to reduce bank erosion, preventing excess sediment from entering the stream. Increased bends in the stream better catch excess sediment deposited downstream, reducing the amount of sediment impacting larger rivers (Kassa et al. 2023).
- **Supports wildlife:** Stream restoration creates a diversity of habitats, providing shelter for juvenile fish. This increases the species richness in the stream, with both species that prefer the open water and sheltered coves now able live in the same stream channel (Lorenz et al. 2013). Anthropogenic barriers in streams are major impediments to genetic diversity in fish species, with the barriers dividing populations into distinct subgroups. This results in genetic drift, where the subpopulations show less resemblance to each other over time. Removing these barriers restores interbreeding amongst the subpopulations, infusing new genes into the gene pool and strengthening the evolutionary capacity of the species (Raeymaekers et al. 2008).

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 stream restoration are included here.

- **Expense:** Some studies have shown that high stream restoration costs may not always be offset by the benefits provided, especially when gray infrastructure alternatives are possible (Kenney et al. 2012).
- **Capacity**
- **Public opinion:** Stream restoration projects that do not include sufficient stakeholder engagement and community buy-in are often less successful (Murphy et al. 2022)
- **Conflict with other land uses:** Form-based restoration is the most popular approach to stream restoration in the United States because all the work can be done within the stream channel, with no changes to the surrounding land uses. However, process-based restoration has seen greater success because it is better equipped to deal with the sources of stream degradation. This involves changing land use practices adjacent to the stream, such as farming or development, which has more economic downsides than form-based restoration (Hawley 2018).
- **Regulation**
- **Lack of effectiveness data:** Consistent monitoring of appropriate metrics that determine project success for river and stream restoration is rare (Bernhardt et al. 2005).

Ecological

- **Failure to understand and address ecological stressors:** Some common pitfalls in river and stream restoration that can cause a project not to perform as expected include creating habitat types outside a site's natural potential, not stabilizing habitat features, and restoring habitats that get overwhelmed by system drivers that were not addressed through the restoration (Beechie et al. 2010).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Trail Creek Forest Service Project	Gunnison National Forest, CO	US Department of Agriculture Forest Service, National Forest Foundation, American Rivers	Process-based restoration including installation of 32 BDAs, 12 sod speedbump structures, 18 woody material structures	0.5 miles	Not provided	1	Using process-based restoration to restore a stream that had become a simplified narrow channel with 1-to-2 ft bank incisions and to rewet valley-wide wetlands. The project aimed to slow water moving through the watershed, with goals of recharging the local aquifer, contributing to late season flows, increasing biodiversity, and decreasing drought impacts on downstream communities.	No	No
Stream Restoration of the Lake Julia Outfall (Reasonover Creek)	DuPont State Forest, NC	North Carolina Forest Service	A new stream channel was established and water control structures were installed using boulders and large logs. Trees were planted in a nearby floodplain forest	600 feet of stream	>$150,000	2	A segment of the creek was rerouted in the 1950s and, over time, had undercut a 30 ft, bare-soil embankment that was collapsing and adding excessive sediment into the stream. (Additional source.)	No	No

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Chilogatee Stream Restoration Project	Great Smoky Mountains National Park, TN	**National Park Service,** Tennessee Stream Mitigation Program	Establishing a new stream channel as well as recontouring other sections of the stream, in addition to planting native seeds and seedlings in riparian areas. Large boulders and logs were used to help reconstruct the stream channel.	4,600 linear feet	Not provided	Not provided	The stream had been degraded from riparian forest clearing, channel relocations, and unrestricted livestock access prior to the site's inclusion in the national park. The project goals were to restore natural stream morphology, connectivity of the stream to the floodplain, create healthy aquatic habitat, and reduce sediment input.	No	Adaptive management plan is located in this source document.

Bolding indicates DOI affiliates.

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Multiple Habitats
26. Invasive and Nuisance Pest and Pathogen Removal

DEFINITION

An *invasive* or *nuisance pest* is synonymous with a species that causes harm to humans or the environment (USGS n.d.b). Unlike invasive species, *nonnative species* are organisms that do not occur naturally in an area but do not necessarily cause harm. Nonnative species are typically introduced to areas by humans (NPS 2020). This summary focuses specifically on invasive and nuisance insects and pathogens. *Invasive pathogens* are bacteria, fungi, or viruses that enter habitats to which they are not native and pose disease risks. Invasive pathogens can be particularly devastating if the host species has not been introduced to the particular type of pathogen (USGS n.d.a). Invasive pathogens are a substantial cause of death for tree species in particular (Haight et al. 2011). Invasive insect incursions are typically low-probability but high-consequence events that can cause ecological, economic, and aesthetic devastation (Venette and Hutchinson 2021). Many invasive insects come to the United States after hitchhiking on plant material originating in other countries (Hill et al. 2016). Nuisance species can either be native or nonnative, but always cause ecological or economic harm (Gwise 2021). Both invasive and nuisance insects and pathogens can be extremely destructive and, in most cases, human intervention of some kind is necessary.

TECHNICAL APPROACH

Integrated pest management (IPM) is the primary approach to managing invasive and nuisance pests in environmentally sound ways. IPM focuses on nonchemical treatments first—methods that align with a nature-based approach—but moves to chemical control as a last resort (University of California 2016).

Although invasive threats are unique to each region, some of the top invasive insects in the United States include the Asian citrus psyllid (*Diaphorina citri*), Asian longhorned beetle (*Anoplophora glabripennis*), coconut rhinoceros beetle (*Oryctes rhinoceros*), emerald ash borer (*Agrilus planipennis*), European cherry fruit fly (*Rhagoletis cerasi*), European grapevine moth (*Lobesia botrana*), hemlock woody adelgid (*Adelges tsugae*), imported fire ant (*Solenopsis invicta*), khapra beetle (*Trogoderma granarium*), Mediterranean fruit fly (*Ceratitis capitata*), Mexican fruit fly (*Anastrepha ludens*), Old World bollworm (*Helicoverpa armigera*), oriental fruit fly (*Bactrocera dorsalis*), spongy moth (*Lymantria dispar*), and spotted lanternfly (*Lycorma delicatula*) (USDA n.d.c). Some of the top invasive pathogens include sudden oak death (*Phytophthora ramorum*), laurel wilt (*Raffaelea lauricola*), white pine blister rust (*Cronartium ribicola*), chestnut blight (*Cryphonectria parasitica*), Dutch elm disease (*Ophiostoma spp.*), butternut canker (*Ophiognomonia clavigignenti-juglandacearum*), and white-nose syndrome (*Pseudogymnoascus destructans*) (USFS n.d.a; National Wildlife Health Center 2018).

While nuisance insects are native, they can still cause harm. Some examples include the southern pine beetle (*Dendroctonus frontalis*), mountain pine beetle (*Dendroctonus ponderosae*), western pine beetle (*Dendroctonus brevicomis*), and spruce budworms (*Choristoneura spp.)*. Some of the common native nuisance pathogens include armillaria root rot (*Armillaria spp.*), Swiss needle cast (*Phaeocryptopus gaeumannii*), and sycamore anthracnose (*Apiognomonia veneta*) (USFS n.d.b).

The steps for combating invasive and nuisance pests and pathogens are as follows:

1. **Prevention:** With any invasive or nuisance species, the most cost-effective approach is always to prevent their spread; both pests and pathogens can be challenging to control once established (McLaughlin and Dearden 2019). Prevention includes any activity that prevents a pest from becoming established. These methods may include removing pests' food, water, or shelter sources or blocking their access (University of California 2016).
2. **Early detection:** Early detection and rapid response is a method that involves coordinated efforts to eradicate invasions before they can spread (USDA n.d.b). There are new detection methods currently available that scientists can use to detect nonnative insects before they become invasive (McLaughlin and Dearden 2019). Early detection can be achieved through coordinated monitoring, surveying, and reporting efforts. Rapid response involves species-specific actions aimed at eradicating early invasions. Quarantining is a method that is often implemented in the rapid response phase. It can be crucial to quarantine a newly invaded area by aiming to close off potential pathways of further spread (DOI 2016).
3. **Eradication:**
    - **Cultural controls:** *Cultural controls* include any activity that discourages pest invasion. Activities include good sanitation and gear cleaning, safely removing infested material, and using pest-resistant plants in farms, homes, parks, and other outdoor spaces (University of California 2016). Cultural controls also include any method implemented to change human behavior to increase awareness of invasive species (USDA n.d.b).
    - **Physical or mechanical controls:** *Physical or mechanical controls* include directly removing pests from plants or using barriers (Figure 1, University of California 2016). Another manual control strategy is removing host trees that are already severely affected (USDA 2021).
    - **Biological controls:** *Biological control* is a method in which beneficial organisms or natural predators are used to manage pests (University of California 2016). It is essential to ensure that, when using biological control methods, only native predators be involved (USDA n.d.b).
    - **Chemical controls:** While chemical controls are not recommended because of their negative effects on the rest of the ecosystem, they are sometimes necessary, and there are ways to make chemical use more environmentally friendly (Figure 2). Pesticides can be very effective in reducing invasive insect invasions, but it is crucial to ensure their use is absolutely necessary and, when possible, avoid the use of broad-spectrum pesticides (University of California 2016).

Figure 26.1 Hanging a spruce budworm trap in Alaska

Photo courtesy USDA Forest Service, Alaska Region

4. **Monitoring**: Monitoring invasive and nuisance species invasions is crucial to long-term management. Monitoring aids in future pest and pathogen management decisions and allows for further learning about site-specific management needs. It also helps reduce project costs by increasing knowledge about the successes and failures of past management (Flint 2012).

Figure 26.2 Verbenone pouches to protect whitebark pines from mountain pine beetles

Note: Verbonene is a synthetic pheromone that indicates to the beetles that the tree is already at capacity and there is not enough food for additional beetles.

Photo courtesy USDA Forest Service, Region 6

OPERATIONS AND MAINTENANCE

The process of detection and prevention will need to continue over time to prevent reintroductions or reinvasions of nuisance or invasive pests and pathogens. In some cases, long-term management will be required to contain and prevent spread.

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Terrestrial habitat:** Studies show that terrestrial systems are the most economically impacted by invasive and nuisance species, specifically because of crop and timber yields that rely on healthy systems (Crystal-Ornelas et al. 2021).
- ✓ **Sites with new establishment:** The International Union for Conservation of Nature recommends prioritizing sites with newly established invasive or nuisance insects and pathogens when working toward eradication (IUCN 2000).

- ✓ **Sensitive sites:** Management is often focused on sites that are particularly vulnerable to invasive species, such as protected areas (McGeoch et al. 2016).
- ✓ **High likelihood of invasion:** Managers can use maps to estimate pathways and potential invasion threats for particular species and, with that information, can try to prevent invasion (McGeoch et al. 2016).
- ✓ **Destructive invasive or nuisance species:** Many prioritization methods focus on the potential negative impacts of the invasion, typically focusing on the traits that most adversely affect the economy, society, ecosystem, or native species (McGeoch et al. 2016).
- ✗ **Lack of resources:** If the agency does not have the time or resources to conduct invasive or nuisance species management at a site, even if all the other site priorities are met, management cannot be implemented (McGeoch et al. 2016).

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?
US Department of the Interior (DOI) Training Related to Invasive Species Management	Document	2021	DOI	National	This resource provides information on training opportunities within the DOI to inform invasive species management.	✓	✓	✓	—
National Plant Diagnostic Network	Website	2002	National Plant Diagnostic Network	National	This website provides information for each state's plant diagnostics lab(s), which aim to support the health and productivity of plants affected by pests and pathogens.	✓	—	✓	—
A National Road Map for Integrated Pest Management	Document	2018	US Department of Agriculture (USDA)	National	This document provides information on IPM principles and focal landscapes for different federal agencies.	✓	—	✓	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
US DOI Funding Guide for Invasive Species Management	Document	2022	DOI	National	This funding guide gives information on funding sources through the DOI for invasive species projects.	✓	—	—	—
Safeguarding America's Lands and Waters From Invasive Species	Guidebook	2016	DOI	National	This resource provides information on implementing a national framework for early detection and rapid response.	✓	✓	✓	✓
EDDMapS	Website	2005	University of Georgia	National	This website allows people to report invasive species, monitor current distribution, learn about management methods, and get species information.	✓	✓	✓	✓
Assessing and Managing Invasive Species within Protected Areas	Guidebook	2009	The Nature Conservancy	National	This guide provides information on managing invasive species for biodiversity within protected areas. This guide is meant for practitioners.	✓	✓	✓	✓
Invasive Species: Alaska	Website		Safeguarding America's Lands and Waters from of Fish and Game	Alaska	This website provides information on invasive species within Alaska and how to manage, prevent, and report them.	✓	—	✓	✓
Invasive Species Strategic Plan 2021-2025	Report	2021	DOI	National	This document provides information on DOI's plans for invasive species management throughout the different bureaus and agencies.	✓	✓	✓	✓
Invasive Species List	Website	2022	USDA National Invasive Species Information Center	National	This website provides a list of registered invasive species within each state and the regulations accompanying them.	✓	✓	—	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Cohesive Approach for Invasive Species Management in the Northeastern U.S.	Guidebook	2007	USDA Forest Service (USFS)	Northeastern United States (20 states bounded by Minnesota, Maine, West Virginia, and Missouri)	This guide is meant to help facilitate collaboration, create management plans, and conduct targeted actions plan for invasive species in the northeastern United States.	✓	—	✓	✓
A Land Manager's Guide to Best Management Practices (BMPs) to Prevent the Introduction and Spread of Invasive Species	Guidebook	2011	The University of Georgia Center for Invasive Species and Ecosystem Health	National	This document provides best management practices for land managers to prevent the introduction and spread of invasive species.	✓	✓	✓	✓

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Carbon storage and sequestration:** Invasive species that target trees can lead to the release of carbon dioxide. Therefore, managing for these invasive and nuisance insects and pathogens can reduce the release of carbon and increase carbon sequestration (Fei et al. 2019).

Social and Economic

- **Agriculture and timber yields:** Invasive insects and pathogens can lead to mass mortality of crop and timber yields, so management is essential for the preservation of these industries (Huber et al. 2002).

- **Cultural values:** Invasive insects and pathogens can have aesthetic effects on different ecosystems. Management of these pests can preserve the aesthetic values of land and waterscapes (Raffa et al. 2023).
- **Food security:** Because of invasive and nuisance insects and pathogens' effect on crops, it is crucial to manage these invasive species to ensure food security within the United States. It is estimated that invasive insects and pathogens cause $40 billion in crop damage annually (USDA 2023).
- **Jobs:** While limited personnel is an often-reported challenge of managing invasive and nuisance insects and pathogens, this also means there are potential job opportunities in this sector (Beaury et al. 2020).

Ecological

- **Enhanced biodiversity:** Invasive and nuisance pests and pathogens are one of the leaders in the destruction of biodiversity and can often lead to species extinction (Hanley and Roberts 2019). Removing them thus boosts biodiversity.

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 invasive and nuisance pest and pathogen removal are included here.

- **Expense:** In 2022, DOI allocated $18,525,500 toward invasive species management projects (USDA n.d.a). Though the remediation investment is high, invasive insects annually cost North America an estimated $27.3 billion in goods and services alone (Bradshaw et al. 2016). In 2005, it was estimated that invasive insects and pathogens resulted in an annual loss of $40 billion for crop and forest production in the United States (Paini et al. 2016).
- **Capacity:** Land managers have reported that they cannot effectively manage invasive species due to limited staff and funding (Beaury et al. 2020).
- **Public opinion**
- **Conflict with other land uses**
- **Regulation**
- **Lack of effectiveness data**

Community

- **Increase in trade:** As global trade increases, presence of invasive and nuisance insects and pathogens will also increase, making management even more challenging (Klapwijk et al. 2016).

Ecological

- **Pesticide use:** Chemical methods of removal of invasive species can adversely affect the ecosystem. It is crucial only to implement this method when absolutely necessary and to avoid broad-spectrum pesticides when possible (University of California 2016).
- **Climate change:** Climate change will affect the distribution of both invasive and nuisance insects and pathogens throughout the United States. For species that are cold-limited, they will be able to spread northward as a result of the warming climate (Dukes et al. 2008). The number of invertebrate pests has also risen with rising temperatures, which will likely continue to increase (Hanley and Roberts, 2019). Climate change adds more challenges to invasive species management, so it is important to observe trends and manage them accordingly.
- **Biological control targeting other species:** In some cases, when using biological control methods or natural predators, these species can target species other than the intended one(s), disrupting the ecosystem. It is crucial to do plenty of research prior to implementing biological control methods (USDA n.d.b).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Collins Emerald Ash Borer (EAB) Management and Response Plan	Fort Collins, CO	City of Fort Collins	3-year ash treatment rotation; IPM	67,000+ ash trees	$7 per trunk inch diameter	Ongoing (began in 2021)	This project is the new management plan for the City of Fort Collins' ash trees. They are implementing different techniques to try to limit the spread of the emerald ash borer.	Carbon and biodiversity loss	No
Winning the Dutch Elm Disease Battle: Developing Resistant Elms for Minnesota	Minnesota	University of Minnesota	Propagating disease-resistant American elms	Not provided	$233,924	Ongoing	This project aims to propagate trees that appear to be resistant to Dutch elm disease, an invasive pathogen. These trees will then be brought back into the natural landscape.	Biodiversity loss.	No
Chicago vs. The Asian Longhorned Beetle: A Portrait of Success	Chicago, IL	The City of Chicago, Illinois Department of Agriculture	Public outreach, education and involvement, cut down and replaced trees, chemical treatment, containment or quarantine	Total not provided	$480,000 (from USFS), along with matching donations (Poland et al. 1998)	1999-2004	This project began with the introduction of the Asian longhorned beetle in Chicago. Managers used chemical and mechanical treatments to eradicate the species.	Biodiversity loss	Chicago had information from 2 years of New York City eradication efforts and had success learning from their struggles.

Bolding indicates DOI affiliates.

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Multiple Habitats
27. Invasive and Nuisance Plant Species Removal

DEFINITION

An *invasive* or *nuisance pest* is a species that causes harm to humans or the environment (USGS n.d.). Unlike invasive species, *nonnative species* are organisms that do not occur naturally in an area but do not necessarily cause harm. Nonnative species are typically introduced to areas by humans (NPS 2020). *Nuisance species* can either be native or nonnative, but they always cause ecological or economic harm (Gwise 2021). This summary focuses on invasive plant species. In 2012, there were an estimated 5,000 nonnative plant species within the United States. While not all are invasive, there is still potential for these plants to spread and cause harm (Kerns and Guo, 2012). Management of invasive and nuisance plant species can benefit both the ecosystem and the economy (Gwise 2021).

TECHNICAL APPROACH

The most effective management practice for invasive and nuisance plants is to prevent species introduction in the first place. Beyond preventing the introduction, many different removal techniques are employed throughout the United States, and early management is crucial to eradicate or control invasive plant species (Bethke et al. 2018). Integrated pest management is the current approach recommended by the US Environmental Protection Agency to manage all invasive and nuisance pests. This approach is an effective and environmentally sensitive method that prioritizes tactics with the least economic costs and harm to humans and the environment, focusing on nonchemical treatments first and using chemical control as a last resort (EPA 2023, University of California 2016). The technical approaches to controlling invasive plants vary depending on the stage of invasion. Across all stages, it is crucial to create interagency partnerships along with collaborations with private landowners because of the cross-boundary nature of invasive and nuisance plants (Kurth 2017).

The steps for combating invasive and nuisance plants are as follows:

1. **Prevention:** With the increase in globalization, the potential for the introduction of invasive species increases. Prevention is the most cost-effective management strategy, and many methods exist to prevent invasive and nuisance plant species invasions (Kurth 2017). Some important prevention methods include effective education on firewood use, ornamental plants, invasive species removal from public and private property, and how not to transport invasive species when traveling (Bethke et al. 2018). Methods specifically for land managers include reducing soil disturbance and revegetating the soil with native species, cleaning equipment when changing watersheds, and preventing the introduction of invasives after prescribed burns (Moorehead et al. 2011). Modeling the risk of invasion that various species pose, especially considering climate change, helps to inform rapid risk screening reports that can help determine the best course of action for managing a particular species (Kurth 2017).

2. **Early detection:** While prevention is the most important containment method, early detection is the next-best strategy (Kurth 2017). One method used to detect invasive and nuisance species is sampling vegetation along roads, trails, power line corridors, and other highly trafficked areas. Maintaining a priority list for species with the highest spread potential or with the most devastating impacts is essential to manage effectively (NPS n.d.).

3. **Eradication:** To eradicate invasive and nuisance plant species before they are not containable, early detection and rapid response is crucial (DOI 2021). Removal methods include the following:

    - **Manual/mechanical removal:** Mechanical removal, including pulling and digging, is often the first method used for invasive species removal (Figure 1). Mechanical methods typically do not require specific licensing but may require permits. Although mechanical removal can be effective if the invasion is early and in small quantities, it is extremely labor-intensive and can cause site disturbance, which can lead to reinvasion. It is important to remove the entirety of the root, and this method is easiest in the spring or early summer because of soil saturation. Cutting or mowing can also be effective, but because it does not destroy the roots of the plants, it will take years to be successful and requires a commitment to the process (DOEE 2023).

    - **Cultural control:** *Cultural invasive species management* refers to the manipulations of habitats to increase invasive species mortality and limit its rate of damage. Cultural methods tend to change human behavior through education to effectively prevent, remove, or manage invasive species. Prescribed grazing with farm animals and prescribed burning are both examples of cultural control methods (USDA n.d.).

        - **Farm animals:** There are examples of agencies using farm animals to help control invasive plant species (Figure 2). For instance, at the Travis Air Force Base, goats, and sheep are used to reduce invasive species populations instead of mowing because of the size and accessibility of the area (Schilter-Lowe, 2018). Because animals have different eating preferences, it is essential to know what species will be most effective for grazing the invasive plants in question; the animals may potentially need training on which plants to eat (Bell 2014).

        - **Prescribed burns:** Humans have used fire to manage vegetation for centuries. Prescribed fire can reduce invasive species populations, but the effectiveness of fire on plants varies considerably based on region, species, and growth forms. For example, in the western United States, prescribed fire is most effective on annual species prior to seed maturation or dispersal. Biennial and perennial species, on the other hand, are more challenging to control and cannot be controlled by a single prescribed burn. However, in the eastern United States, management agencies have been successful in managing perennial grasses with prescribed burning. Woody invasive species are often the most difficult to control with prescribed burning because they tend to resprout after burns (DiTomaso et al. 2006).

Figure 27.1 Russian olive removal on a US Air Force base in North Dakota

Photo courtesy USFWS Mountain-Prairie

    - **Mulching:** Mulching can be used to block light from invasive and nuisance plant species and is typically done with a combination of mulch and cardboard to fully cover the invasive or nuisance ground cover. Blocking the light prevents germination and growth (Manning and Miller, 2011).

- **Biological control:** *Biological control methods* refer to the use of native or natural enemies to weaken, kill, or stop seed production of invasive and nuisance plant species. It is important to do extensive research on the species and method

Figure 27.2 Releasing goats at the Bozeman Fish Technology Center to control noxious weeds

Photo courtesy USFWS Mountain-Prairie

intended prior to releasing large numbers of the native species. Species used are typically insects, pathogens, nematodes, and mites that feed upon plants (Miller et al. 2015).

- **Chemical control:** Using herbicides is a very common control method for invasive and nuisance plant management, but it can adversely affect the surrounding ecosystem. Selective herbicide spraying typically has the least impact on the ecosystem due to the ability to target individual plants; it is important to avoid broad-spectrum herbicides as much as possible (DOEE 2023, Miller et al. 2015) When working in wetland zones, there are specific aquatic herbicides that should be used (DOEE 2023).

4. **Containment/long-term management:** If the invasion is beyond the point of eradication, the last management method is containment and long-term management. Containment can include practices such as the removal of above-ground plant parts or restricting the species spread (Miller et al. 2015). Long-term management and containment can be incredibly costly and labor-intensive (DOI 2021).

OPERATIONS AND MAINTENANCE

The process of detection and prevention will need to continue over time to prevent reinvasions or reintroductions of invasive and nuisance plants. As described previously, long-term management will be required to contain and prevent the spread of these plants in some cases.

FACTORS INFLUENCING SITE SUITABILITY

Because invasive and nuisance species plague most of the land in the United States to some extent, the most crucial aspect of site suitability is prioritization to help decide which sites are at the highest risk.

- ✓ **Heavily trafficked areas:** Invasive and nuisance species are typically unintentionally spread by humans, so heavily trafficked sites are often at higher risk of introductions (NWF n.d.).
- ✓ **High-risk invasive species detected:** Using species distribution models is a standard method of determining the invasion risk of particular species in specific regions (Adhikari et al. 2022).
- ✓ **Area at risk of invasion:** Prevention is the most cost-effective management strategy, so it is essential to implement projects in areas at high risk of invasive plant species invasion (Bethke et al. 2018).
- ✓ **Riparian areas:** Riparian areas are often disturbed by humans, which puts them at higher risk for species invasions (Hammer 2019).
- ✓ **High biodiversity:** It is important to preserve biodiversity when possible; this is often the goal of invasive species management projects. Determining high-biodiversity areas is crucial in prioritizing project implementation (Tu 2009).
- ✓ **Stage of the plant life cycle:** It is important to know the life cycle of the plant that is being managed or eradicated. According to research, annual plants should be pulled and cut at the soil and chemically treated before flowering. Biennial plants should be pulled and dug out in the first year, repeated cutting should be implemented in the second year. Biennial plants should be chemically treated before emergence in the first year and during the rosette stage; in the second year, they should be treated before flowering. Noncreeping herbaceous perennials should be dug, cut, pulled, and treated with herbicide at full canopy but before the seed is set. Creeping herbaceous perennials should be cut and chemically treated in the late season. Nonsuckering woody species should be cut and chemically treated when at full canopy (May/June) to fall. Suckering woody species should be chemically treated between July to fall. Woody vines should be cut any time of the year and chemically treated eight weeks after cutting (Rojik 2023).

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?
Executive Order 13751	Document	2016	Executive Office of the President	National	This order explains the duties to be performed by all federal agencies to limit the impacts of invasive species throughout the United States.	✓	—	—	—
A Management Guide for Invasive Plants in Southern Forests	Guidebook	2013	US Department of Agriculture Forest Service (USFS)	Southern United States	This guidebook provides information on how to prevent invasive species establishment, maintain native forests, and eradicate invasive species in southern forests.	✓	✓	✓	✓
Land Manager's Guide to Developing an Invasive Plant and Management Plan	Guidebook	2018	US Fish and Wildlife Service, California Invasive Plant Council	National	This guide aids land managers in writing an invasive species management plan and monitoring the outcomes and adaptive management strategies.	✓	✓	✓	✓
Best Management Practices (BMPs) to Prevent the Introduction and Spread of Invasive Species	Guidebook	2011	The University of Georgia Center for Invasive Species and Ecosystem Health	National	This document provides best management practices for land managers to prevent the introduction and spread of invasive species.	✓	✓	✓	✓
Field Guide: Invasive Plant Inventory, Monitoring, and Mapping Protocol	Guidebook	2001	USFS	National	This guide provides a protocol for land managers to monitor, map, and inventory invasive species. This guide aids in collaborative management by providing information that can be shared across jurisdictions. Because it is an older resource, the technical mapping data may be outdated.	✓	✓	✓	✓

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Cohesive Approach for Invasive Species Management in the Northeastern US	Guidebook	2007	USFS	Northeastern United States (20 states bounded by Minnesota, Maine, West Virginia, and Missouri)	This guide is meant to help facilitate collaboration, create management plans, and conduct targeted actions plan for invasive species in the northeastern United States.	✓	—	✓	✓
Midwest Invasive Plant Network: Invasive Plant Control Database	Website	2018	Midwest Invasive Plant Network	Midwest United States	This database provides information on control techniques, examples of projects, method effectiveness, and handbooks/other resources.	✓	✓	✓	✓
Invasive Species List	Website	2022	US Department of Agriculture National Invasive Species Information Center	National	This website provides a list of registered invasive species within each state and the regulations accompanying them.	✓	✓	—	—
Invasive Species: Alaska	Website	n.d.	Alaska Department of Fish and Game	Alaska	This website provides information on invasive species within Alaska and how to manage, prevent, and report them.	✓	—	✓	✓
Invasive Species Strategic Plan 2021-2025	Document	2021	US Department of the Interior (DOI)	National	This document provides information on DOI's plans for invasive species management throughout the different bureaus and agencies.	✓	✓	✓	✓
Bureau of Land Management's (BLM's) National Invasive Species Information Management System (NISIMS)	Website	2023	US Geological Survey (USGS)	Mostly western states (anywhere with BLM land)	This dataset provides standardized information on invasive species (currently only weeds, but will expand to all invasive taxa).	✓	✓	✓	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
The Use of Fire as a Tool for Controlling Invasive Plants	Book	2006	California Invasive Plant Council, Joint Fire Science Program, USGS	National	This book describes methods for using prescribed fire as a control method for invasive plant species.	✓	✓	✓	✓
Field Guide for Managing Cheatgrass in the Southwest	Guidebook	2017	USFS	Southwest United States	This guide gives actionable information on how to manage invasive cheatgrass.	✓	✓	✓	✓
EDDMapS	Website	2005	University of Georgia	National	This webpage allows people to report invasive species, monitor current distribution, learn about management methods, and get species information.	✓	✓	✓	✓
Assessing and Managing Invasive Species within Protected Areas	Document	2009	The Nature Conservancy	National	This guide provides information on managing invasive species for biodiversity within protected areas. This guide is meant for practitioners.	✓	✓	✓	✓
Invasive Aquatic Plant Control and Management Guide	Guidebook	2015	Michigan Lake and Stream Associations	Midwest	This guide provides information on invasive aquatic plant management.	✓	✓	—	—

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Reduced wildfire risk:** Invasive and nuisance plant species, especially grasses, increase the severity of wildfires because of their high flammability. Many of these grasses grow and dry out quickly; the species of particular concern within the United States are cheatgrass (*Bromus tectorum*), cogon grass (*Imperata cylindrica*), and buffelgrass (*Cenchrus ciliaris*). Effectively managing these grasses can help reduce catastrophic wildfires (Cornwall 2022).

- **Drought mitigation:** Invasive and nuisance species often require more water than native species; therefore, invasive species management can help reduce drought stress (White House 2022).

Social and Economic

- **Food security:** Invasive and nuisance plant species can affect food security because of their negative impact on crop and animal health (IUCN 2021). Within the United States in 2001, weeds (45% of which were invasive species) caused a $33 billion loss in revenue from agriculture (Pimental et al. 2001).
- **Agriculture and timber yields:** Invasive and nuisance species such as buckthorn and honeysuckle can reduce tree growth, leading to losses in timber sales. Managing these species can therefore safeguard timber profits (Wisconsin DNR). As noted previously, nuisance and invasive weeds also cost billions of dollars in agriculture revenue (Pimental et al. 2001).

Ecological

- **Enhanced biodiversity:** Invasive and nuisance species are one of the biggest known threats to biodiversity (Hanley and Roberts 2019, Allendorf and Lundquist 2003). Invasive plant species are known to out-compete, hybridize with, or alter the ecological community of native plants, which reduces local biodiversity and can lead to extinction (Morse et al. 2004). Invasive species have contributed to the decline of 42% of endangered or threatened species (Kurth 2017). Biodiversity is crucial in supporting a functioning ecosystem and can lead to a loss of the value of ecosystem services provided by forests (Smith and Webber, 2017).
- **Supports wildlife:** Invasive and nuisance plant species can negatively affect habitat and food supply for native animals and insects (National Wildlife Federation n.d.).

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 invasive and nuisance plant species are included here.

- **Expense:** In 2020, DOI invested $143 million into invasive species management. Cheatgrass, a species plaguing the western United States, cost $18 million to remediate from 2015–2019 within lands managed by DOI (2021). Invasive species management does not typically lead to complete eradication, so perpetual management is often needed, which is extremely costly (DOI 2023).
- **Capacity:** Invasive and nuisance species management often requires a lot of human capacity to succeed. Managers often have to put all resources into current invasion management. They are limited in the time and resources to prevent new invasions, which is the most cost-effective management method (Beaury et al. 2020).

- **Public opinion**
- **Conflict with other land uses**
- **Regulation**
- **Lack of effectiveness data**

Community

- **Ornamental plants:** There are still many invasive and nuisance species being sold throughout the country, typically as ornamental plants. This is the primary pathway for invasive species to enter the United States. Advocating for federal regulation and cohesive local policies for preventing invasive species sales is essential to avoid disjointed state rulings (Beaury et al. 2021).

Ecological

- **Climate change:** The influence of climate change on invasive and nuisance species management concerns many land managers. Climate change affects the distribution and abundance of invasive plant species, and more challenges are likely to appear (Beaury et al. 2020). Because invasive and nuisance plant species are resilient because of their high dispersal rates, rapid growth rates, and high tolerance to environmental conditions, they will likely be able to adapt easier to changing conditions as a result of climate change (Finch et al. 2021).
- **Site disturbance:** Manual or mechanical invasive and nuisance species removal can disturb the ecosystem, which can lead to reinvasion if not appropriately managed (DOEE 2023). Soil disturbance, erosion, or loss can also be caused by clearcutting or mowing invasive species, but if managed with root retention in smaller areas, erosion can be minimized (Castillo and Smith-Ramírez 2018).
- **Chemical use:** Herbicides can negatively impact all species, including humans. Broad-spectrum herbicides are often used, which can be toxic to native species and create resistance in some invasive and nuisance plants. Herbicides can also impact the environment by contaminating waterbodies if they infiltrate through runoff or misguided application, changes in soil composition, and killing native predators. Herbicides can negatively impact livestock, fisheries, and wildlife through exposure (EPA 2023). Lastly, herbicides can have adverse effects on human health through direct or indirect exposure, including reproductive, liver, and kidney issues (Myers et al. 2016).
- **Biological controls:** Biological controls can result in attacks on native species when not adequately researched and planned, such as the musk thistle weevil's assault on both invasive and native species. It is crucial to perform thorough research before implementing this approach (Miller et al. 2015)

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Invasive Plant Management Support at Minute Man National Historical Park	Minute Man National Historical Park, MA	National Park Service (NPS)	Mechanical treatment, chemical treatment	1,038 acres	$82,446 ($15,000 grant plus an additional $67,446)	1 year (1 field season)	This project focused on the removal of 12 different invasive plant species throughout one field season.	Loss of biodiversity	No
Gunnison Basin Cheatgrass Implementation Project	Gunnison Basin, CO	US Fish and Wildlife Service, Colorado Parks and Wildlife, Partners for Fish and Wildlife, Upper Gunnison River Conservancy District, BLM, Colorado Field Ornithologists, Gunnison County Stockgrowers, USFS, Bird Conservation of the Rockies	Wet meadow restoration, cheatgrass treatments, sagebrush restoration	150 acres (wet meadow restoration), 1000 acres (cheatgrass treatment)	$793,476 (2023)	Ongoing (began 2022)	This project is designed to remove cheatgrass and restore sagebrush in the Gunnison Basin.	Promote biodiversity	No

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Removing Invasive Plants from the Great Meadow	Acadia National Park, ME	NPS	Manual removal (hand saws and pruners), herbicide	116 acres	Not provided	Ongoing (began 1989)	The invasive plant management program in Acadia National Park aims to remove glossy buckthorn and restore native wetland species to combat climate change and increase biodiversity.	Restore native plant communities	They adapted the project to not completely eradicate glossy buckthorn because of capacity limitations but instead to focus on restoring native species.
Weed Control Along Minnesota Roadsides	Minnesota	Minnesota Department of Transportation	Prevention and early detection through monitoring, cleaning equipment, managing ground disturbance, and maintaining healthy roadside native vegetation; control through mowing, herbicide, biological control, and prescribed fire; containment through containing the spread	175,000 acres	Not provided	Ongoing	This project is an ongoing management strategy that prioritizes prevention, control, and containment.	Maintain native species, limit the further spread of invasive species	This project has asked for public help in monitoring and detection.

Bolding indicates DOI affiliates.

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Multiple Habitats
28. Invasive and Nuisance Wildlife Removal

DEFINITION

An *invasive* or *nuisance pest* is a species that causes harm to humans or the environment (USGS n.d.). Unlike invasive species, *nonnative species* are organisms that do not occur naturally in an area but do not necessarily cause harm. Nonnative species are typically introduced to areas by humans (NPS 2020). *Nuisance species* can either be native or nonnative, but they always cause ecological or economic harm (Gwise 2021). This summary focuses on invasive animal species. Invasive and nuisance animal species can alter ecological systems and kill, suppress, compete with, or displace native species, adversely impacting biodiversity (Tu 2009). Invasive animals are present in more than half of all US National Parks (Dayer et al. 2019). Invasive and nuisance wildlife have different environmental effects and management techniques, but there are similarities in planning and implementing control and removal projects.

TECHNICAL APPROACH

Integrated pest management is one of the primary approaches for managing invasive and nuisance wildlife, and it is a sustainable and environmentally sound invasive management framework that aims to minimize the harmful effects of invasive and nuisance wildlife species (USDA 2018).

As with all invasive and nuisance species, prevention is the most cost-effective and efficient management practice for invasive and nuisance wildlife (NPS 2021). Some of the common invasive and nuisance terrestrial wildlife in the United States are brown tree snakes (*Boiga irregularis)*, Burmese pythons (*Python molurus bivittatus*), European starlings (*Sturnus vulgaris*), and wild boar (*Sus scrofa*) (USDA n.d.c, Dayer et al. 2019). Some of the most common invasive and nuisance aquatic wildlife in the United States include red lionfish (*Pterois volitans*), quagga mussels (*Dreissena rostriformis bugensis*), bighead carp (*Hypophthalmichthys nobilis*), cane toad (*Rhinella marina*), Nile perch (*Lates niloticus*), and nutria (*Myocastor coypus*) (Dayer et al. 2019; USDA n.d.b). Terrestrial and aquatic invasive and nuisance wildlife can be introduced through various mechanisms, usually involving humans, and intentionally or unintentionally. Mechanisms include species intentionally imported as pets, for consumption, ornamental ponds, or research, and unintentionally by stowing aboard vessels, aircraft, and vehicles (USFWS 2020).

The steps for combating invasive and nuisance wildlife are as follows:

1. **Prevention**: To prevent the introduction of invasive animals, it is crucial to understand their movement and introduction potential (NPS 2021). Large-scale prevention usually relies on some form of import and export regulation, border control, and equipment inspections. Some essential prevention methods currently employed

by the Department of the Interior (DOI) include horizon scanning and predictive modeling to find high-risk species and pathways and leveraging the existing Lacey Act for wildlife trade restrictions. The DOI also prioritizes site-specific prevention measures, including educating visitors on invasive species laws (DOI 2021a).

2. **Early Detection/Rapid Response (EDRR):** EDRR is a method used for all invasive species taxa and involves regular site monitoring. A preplanned response is enacted when an invasive or nuisance species is detected (NPS 2021). Some key EDRR methods DOI employs include biosurveillance at high-risk sites, enhancing taxonomic expertise, and citizen science programs (Figure 1, DOI 2021a). The key emphasis of the EDRR framework is timeliness, with the idea that the quicker the species is identified and managed, the less the funding and personnel needs. EDRR is implemented through surveying and monitoring lands and responding with species- and site-specific eradication methods to prevent long-term establishment (DOI 2016).

Figure 28.1 Inspecting a recreational boat for invasive quagga mussels

Note: Boater education is a key part of preventing mussels from spreading between waterways.

Photo courtesy Oregon State University

3. **Long-term control and eradication:** When the first two methods are not successful, and depending on the site and the level of establishment, sometimes complete eradication is not possible. Long-term control and eradication tactics are more expensive than prevention and rapid response (NPS 2021). Some methods for management and eradication include traps, shooting, toxicants, dogs, introduced predators, habitat manipulation, and barriers. The technique depends on the specific taxa being targeted and methods are typically used in concert with one another (Witmer et al. 2007). Manual/mechanical, biological, and chemical control are the main methods employed for invasive and nuisance wildlife species. Manual/mechanical controls can involve hunting, fishing, and trapping (Figures 2 and 3). Biological control can involve the use of sterile organisms to prevent reproduction. Chemical control can involve rodenticides and piscicides. Restoration of the land and native species is another important method that should be included in all strategies (Tu 2009).

Figure 28.2 Hunting invasive lionfish

Photo courtesy Oregon State University

Figure 28.3 US Department of Agriculture (USDA) researcher training other biologists on trapping invasive Burmese pythons in Florida

Photo courtesy USDA

OPERATIONS AND MAINTENANCE

The process of detection and prevention will need to continue over time to prevent reintroductions or reinvasions of invasive and nuisance wildlife. In some cases, long-term management will be required to contain and prevent spread.

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **High-risk invasive species detected:** Management should start as soon as possible when an invasive or nuisance species is detected (DOI 2016).
- ✓ **Area at risk of invasion:** Management and monitoring efforts are often concentrated in areas at higher risk of invasions, often determined by identifying typical invasion pathways (DOI 2016).
- ✓ **High biodiversity:** Sites with high biodiversity are often deemed high-priority landscapes for invasive and nuisance wildlife management (DOI 2016).

- ✓ **Species type:** Invasive and nuisance animal management and control is extremely species-specific and requires different techniques for each individual species. The species present at the site will determine what management techniques are possible (Witmer et al. 2007).
- × **Access:** Invasive and nuisance wildlife species often cover large swaths of land across different jurisdictions and ownerships, so management efforts can be halted if access to the land is not permitted (DOI 2016).

TOOLS, TRAINING, AND RESOURCES FOR PLANNING AND IMPLEMENTATION

						Resource Includes			
Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
US DOI Training Related to Invasive Species Management	Document	2021	DOI	National	This resource provides information on training opportunities within the DOI to inform invasive species management.	✓	✓	✓	—
A National Road Map for Integrated Pest Management	Document	2018	USDA	National	This document provides information on integrated pest management principles and focal landscapes for the different federal agencies.	✓	—	✓	—
US DOI Funding Guide for Invasive Species Management	Document	2022	DOI	National	This funding guide gives information on funding sources through the DOI for invasive species projects.	✓	—	—	—
Safeguarding America's Lands and Waters From Invasive Species	Guidebook	2016	DOI	National	This resource provides information on implementing a national framework for early detection and rapid response.	✓	✓	✓	✓

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
EDDMapS	Webpage	2005	University of Georgia	National	This webpage allows people to report invasive species, monitor current distribution, learn about management methods, and get species information.	✓	✓	✓	✓
Assessing and Managing Invasive Species within Protected Areas	Document	2009	The Nature Conservancy	National	This guide provides information on managing invasive species for biodiversity within protected areas. This guide is meant for practitioners.	✓	✓	✓	✓
Invasive Species: Alaska	Website		Alaska Department of Fish and Game	Alaska	This website provides information on invasive species within Alaska and how to manage, prevent, and report them.	✓	—	✓	✓
DOI Invasive Species Strategic Plan 2021-2025	Document	2021	DOI	National	This document provides information on DOI's plans for invasive species management throughout the different bureaus and agencies.	✓	✓	✓	✓
Invasive Species List	Website	Updated 2022	USDA National Invasive Species Information Center	National	This website provides a list of registered invasive species within each state and the regulations accompanying them.	✓	✓	—	—
Cohesive Approach for Invasive Species Management in the Northeast US	Guidebook	2007	USDA Forest Service	Northeastern United States (20 states bounded by Minnesota, Maine, West Virginia, and Missouri)	This guide is meant to help facilitate collaboration, create management plans, and conduct targeted actions plan for invasive species in the northeastern US.	✓	—	✓	✓
Aquatic Nuisance Species Task Force: 2020 - 2025 Strategic Plan	Document	2020	Aquatic Nuisance Species Task Force	National	The plan outlines government agency strategies to address invasive and nuisance aquatic species.	✓	—	✓	—

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Social and Economic

- **Public health and safety:** Invasive and nuisance species can threaten the safety of both employees and the public within federal lands, so management can provide safer conditions (NPS 2022).
- **Food security:** Invasive and nuisance animal species consume crops, both in field and storage, and livestock. Management efforts can protect these resources and aid food security (Witmer et al. 2007).
- **Jobs:** Invasive species management requires trained site-specific personnel. From 2019 to 2021, the US Fish and Wildlife Service (USFWS) increased the number of teams working on invasive species projects from five to 14. This job increase is one example of the job growth possible with effective invasive species management (USFWS n.d.).
- **Reduced or avoided costs:** Some economic benefits of invasive species management include protecting biodiversity, reducing crop and timber damage, and enhancing ecosystem health. Invasive species management can also reduce diseases. Cost-benefit analyses are essential to ensure the reduction or avoidance of costs (Hanley and Roberts, 2019).
- **Recreational opportunities:** Invasive and nuisance animal species have diminished national parks' recreational value, so effective management can preserve these recreational resources and areas (Dayer et al. 2019).

Ecological

- **Enhanced biodiversity:** Invasive and nuisance species are one of the leaders in biodiversity loss, native species endangered status, and species extinction. Management can help reduce biodiversity loss from these species, and restoration in management practices can enhance native biodiversity (IUCN 2021, Tu 2009).

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 invasive and nuisance wildlife removal are included here.

- **Expense:** In 2022, DOI allocated $18,525,500 toward invasive species management projects (USDA n.d.a). Funding opportunities for invasive and nuisance species management are often focused on plants, insects, and pathogens, so funding opportunities for invasive and nuisance wildlife can be challenging (Witmer et al. 2007).

- **Capacity:** One of the main challenges for invasive and nuisance animal species management is limited capacity and resources. Management is challenging because invasive species are often not dealt with until their impacts are obvious, which implies widespread establishment and requires many more people to manage. To avoid personnel limitations, it is important to have trained managers focus on prevention and EDRR efforts (Dayer et al. 2019).
- **Public opinion:** Invasive and nuisance wildlife management typically receives less funding than plants, insects, and pathogens. Public perception surrounding invasive and nuisance animals is not as strong, and there are more reservations about managing animals if the management is perceived as hurting the species. Education is crucial to gain the support of the public (Witmer et al. 2007).
- **Conflict with other land uses**
- **Regulation**
- Lack of effectiveness data

Community

- **Safety:** Invasive and nuisance animals can bring safety hazards to people and domestic animals, so management can be dangerous. It is essential to be cautious when managing for these species (Witmer et al. 2007).
- **Exotic pets:** Invasive and nuisance wildlife species are often legally introduced to the United States as exotic pets. This enormous industry can make management challenging (Witmer et al. 2007). An example of an invasive species introduced through the exotic pet trade is the Burmese python in Florida (Janos 2018).
- **Access:** Because of the nature of invasive and nuisance wildlife, management is often required across large land areas across various jurisdictions and ownerships. Accessibility and regulations across land areas can vary, making large-scale management challenging (Witmer et al. 2007).

Ecological

- **Chemical use:** Chemicals like rodenticides can be very toxic to humans and the environment. Rodenticides can be ingested by nontarget wildlife, which negatively impacts biodiversity. The EPA has regulated certain chemicals, and it is important to avoid chemical control as much as possible (Center for Biological Diversity n.d.).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Palmyra Atoll National Wildlife Refuge Rat Eradication Project	Palmyra Atoll National Wildlife Refuge	**US Fish and Wildlife (USFWS)**	Chemical control using various rodenticides	618 acres of land and 15,512 acres of lagoons and shallow reefs	Not provided.	Ongoing (began 2011)	This project aims at reducing rat predation on seabirds specifically, as well as plants and terrestrial vertebrates. The project aims to preserve biodiversity and reduce a nonclimate stressor from the island ecotype.	Enhancing biodiversity	Invasive coconut trees took over after rats were eradicated, so the USFWS had to continue forest invasive management. Continued monitoring is crucial to understanding eradication's long-term effects (Hardach 2020).
Quagga-Zebra Mussel Action Plan for Western U.S. Waters	Western United States	The Western Regional Panel on Aquatic Nuisance Species	prevention, EDRR, containment and control, outreach and education, research	Not provided	Not provided	Established in 2010	This project aimed to set up water regulations for the western states. The goals focused on establishing priorities of management actions and serving as a future road map.	Enhancing biodiversity, water quality	No
Chesapeake Bay Nutria Eradication Project	Chesapeake Bay, MD	**USFWS**, US Department of Agriculture Animal and Plant Health Inspection Service Wildlife Services, Maryland Department of Natural Resources	Detector dogs, habitat modification, traps, shooting, chemical controls (ICWDM n.d.).	>250,000 acres	$30 million (Fenston 2020)	>20 years	The impacts of nutria on the Chesapeake Bay region in Maryland devastated marshes and wetlands as a result of their feeding patterns. This project aimed to protect and fully eradicate nutria through various control methods.	Sea level rise, enhance biodiversity	This project is an excellent example of how interagency collaboration is crucial for eradication projects.

Bolding indicates DOI affiliates.

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Multiple Habitats
29. Prescribed Burns

DEFINITION

Prescribed burns are fires that are intentionally set in a controlled manner in accordance with specified weather limitations, laws, policies, and regulations. Prescribed burns are used by management teams with fire expertise to restore health to fire-dependent ecosystems. They are also used to reduce fuel loads to prevent ecosystem and community damage from catastrophic wildfires (USFS 2016, NWCG 2023). Cultural burning has been used by Indigenous people in the United States from time immemorial (Lake 2021). As a result of excessive fire suppression starting in the late 1880s, many ecosystems that relied on fire have been deprived of regular burning crucial to maintaining their ecosystem health. A primary goal of prescribed burning is to bring the fire-adapted ecosystem back to a fire regime consistent with the historical regime (Greco 2018). The Joint Fire Science Program defines a fire regime as "the general temporal and spatial patterns of fire behavior and effects within a particular vegetation type or ecosystem" (Sommers et al. 2019). Prescribed fire as a fuel treatment alongside forest thinning is an effective approach to reducing catastrophic wildfires.

TECHNICAL APPROACH

The National Wildfire Coordinating Group (NWCG) provides *Standards for Prescribed Fire Planning and Implementation* (2022b). These interagency standards offer directions and guidance for prescribed fire planning and implementation for the Department of the Interior's (DOI's) Bureau of Land Management (BLM), Bureau of Indian Affairs, National Park Service, Fish and Wildlife Service (USFWS), and the US Department of Agriculture (USDA) Forest Service (USFS). This document will outline the steps required to conduct prescribed fire on public lands. It is also important to note that combining prescribed burning with thinning projects is critical to achieve many positive outcomes (Hedges 2009)**.**

1. **Determine if the site is a fire-adapted ecosystem that could benefit from prescribed fire (Avitt 2023):** Two web-based tools that can aid in site suitability determination are LANDFIRE and the Interagency Fuel Treatment Decision Support System (IFTDDS) (DOI 2015). LANDFIRE may require more experience with various geographical information systems and fuels data, while the IFTDDS is more user-friendly for those with less technical expertise.

2. **Create a prescribed burn plan:** This process can take up to 12 months to complete (Avitt 2023). Prescribed fire planning and implementation is site-specific, so although there are general guidelines for approaches, each site will differ (Greco 2018). Factors influencing the plan include fuel moisture, forest stand characteristics, historical data, terrain, soil type, and elevation. The plan should also state what type of burn will be conducted (Stubbendieck et al. 2007; Avitt 2023). The two primary types of prescribed burning used are pile burning and broadcast or understory burning. *Pile burning*

refers to burning fuels in a slash pile created from woody debris and vegetation that are not useful for other purposes (Figure 29.1; James 2011, DFPC 2015). These piles are often left to dry out for a few years before they are burned. *Broadcast* or *understory* burning refers to fire being applied to a larger area to burn debris, saplings, and other surface fuels to create less hazardous fuel loads (Figure 2, Rau n.d., BLM n.d.). Within this plan, it is important to include a prescription for thinning treatment to prepare the site for the burn to make fuel management as effective as possible (USFS n.d.b). A long-term study conducted by the USFS, the Lick Creek Demonstration/Research Forest, found that fuel reduction and restoration are most successful when cutting and burning are combined (Hood et al. 2020).

3. **Conduct the burn when conditions match to the burn window described in the burn plan:** The *burn window* refers to when all the environmental, weather, and projected fire behavior model conditions illustrated in the burn plan are met (Avitt 2023). To ensure all conditions are met, a before-action review can be helpful to define what might lead to the project's failure and improve the strategy prior to implementation. The burn can be conducted when the burn window conditions are met and the proper personnel are available. Everyone working on the burn must be adequately trained and carry current qualifications to participate in or lead a

Figure 29.1 Pile burning in Kaibab National Forest

Photo courtesy Kaibab National Forest

Figure 29.2 Understory burning in a grassland at Las Cienegas National Conservation Area

Photo courtesy Dan Quintana, BLM Fuels Program Manager

prescribed burn. Unless local agreements specify otherwise, these qualifications must meet PMS 310-1 standards, which define the criteria wildland firefighters must meet to engage with fire (NWCG 2022).

4. **Monitor the burn, patrol the perimeter, and mop up:** *Prescribed fire monitoring* is the process of repeated observation of weather, fire behavior, fuels, and smoke dispersal throughout the project (NWCG 2022). A prescribed burn requires patrolling the perimeter until the prescribed burn is completely out to ensure the fire does not escape (BLM). Mopping up is required to extinguish or remove burning material to ensure the fire will not spread outside the control lines. Mop-up will include cold trailing (feeling the ground with the back of a bare hand to ensure there is no residual heat), spotting smoke along the perimeter, and exposing heavy fuels to ensure no residual burn (Rizza et al. 2022). Exposing heavy fuels is necessary because there is often heat remaining underneath logs and stumps. Firefighters will employ the same tactics to ensure there is no heat near the control line (USFS n.d.a).

5. **Conduct outcome, technical, and action reviews:** These reviews aim to continually improve prescribed fire programs through individual and organizational learning. Agency administrators will determine which outcome reviews are necessary, but two types are always required if the burn does not follow what was planned: Declared Wildfire Reviews and Air Quality NOV Reviews. The other suggested reviews are Technical On-Site Peer Review, which evaluates the burn plan before and as the burn is being conducted, and the After Action Review, where the crew/team discusses the desired versus actual outcomes and what lessons were learned. More details about the necessary reviews can be found in the NWCG Standards for Prescribed Fire Planning and Implementation (NWCG 2022).

OPERATIONS AND MAINTENANCE

Prescribed burning (and often, associated thinning) will need to be repeated over time to maintain effectiveness. The number of years between fire treatments will differ based on the type and age of a forest.

FACTORS INFLUENCING SITE SUITABILITY

Because prescribed burn site attributes are extremely region-specific, it is essential to reference information specific to each site. Resources like LANDFIRE and IFTDDS can aid in regional decision-making surrounding fuel treatment. Some general site attributes are outlined as follows.

- ✓ **Community buy-in:** Many people are afraid of prescribed burns and do not understand the full benefits of conducting them. It is essential to be transparent about burn plans and create space for education to gain community support. With community support, it is easier to get this work completed (Brenner et al. 2014).
- ✓ **Wildland–urban interface:** The *wildland–urban interface* (WUI) is where a fire-adapted ecosystem and people intersect. Conducting prescribed burns in the WUI is important because this area has the most potential for infrastructure loss and threats to human safety (Cobb 2020).
- ✓ **Wildfire hazards:** An area with potential for extreme wildfire behavior or other hazards is a good location to conduct a prescribed burn in order to mitigate these potential hazards (Greco 2018).
- ✓ **Fire-adapted ecosystems:** Every ecosystem is different, so knowing what the fire needs are within a specific site is essential. Within the United States, the West, Southwest, Great Plains, and Southeast are all considered fire-adapted regions that can significantly benefit from prescribed fire (Avitt 2023).
- ✗ **Strict air quality regulations:** A site adjacent to communities with already compromised air quality or strict air quality guidelines may not be suitable for a prescribed burn (NWCG 2018).
- ✗ **Burn window limitations:** Some regions have minimal burn windows, which makes it challenging to conduct prescribed burns (Avitt 2023).
- ✗ **Sandy soils:** Prescribed fire should be used on sandy soils only with extreme caution because of a higher likelihood of erosion (Stubbendieck et al. 2007).

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?
Standards for Prescribed Fire Planning and Implementation	Guidebook	2022	NWCG	National	This report outlines the required standards for DOI and USDA for any prescribed burn activity.	✓	✓	✓	—
Prescribed Fire Template, PMS 484-1	Document	2021	NWCG	National	Provides a template of the information needed to implement a prescribed burn plan.	✓	—	—	—
Facilitating Prescribed Fire in Northern California through Indigenous Governance and Interagency Partnerships	Journal Article	2021	Tony Marks-Block and William Tripp	Written for California but much of the information is broadly applicable	Discusses how to facilitate an expansion of prescribed burning with Indigenous groups and federal agencies	✓	—	—	✓
Indigenous Fire Stewardship: Federal/Tribal Partnerships for Wildland Fire Research and Management	Journal Article	2021	Frank Kanawha Lake	National	Describes the relationship and knowledge that Indigenous tribes bring into the fire space, how to integrate Indigenous knowledge, and how to decolonize the wildland fire space.	✓	✓	—	—
Confronting the Wildfire Crisis	Guidebook	2022	USFS	National	This strategy outlines the USFS's interagency approach to confronting the wildfire crisis. It touches on collaborative burn strategies more broadly.	✓	✓	—	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Habitat Management Fact Sheet: Prescribed Burning	Document	2005	Indiana Division of Fish and Wildlife	Written for Indiana but much of the information is broadly applicable	This is a step-by-step guide to conducting a prescribed burn from start to finish, with habitat management as the primary goal. It also offers specific technical guidelines.	✓	✓	✓	—
Colorado Prescribed Fire Planning and Implementation Policy Guide	Guidebook	2019	Colorado Division of Fire Prevention and Control	Written for Colorado but much of the information is broadly applicable	Provides a guide to planning and implementing a prescribed burn and reviewing the burn after it is complete.	✓	✓	✓	—
Southeast Prescribed Fire Initiative	Website	2023	Southeast Regional Partnership for Planning and Sustainability	Southeast United States	The website contains materials that provide information on liability, burning in longleaf stands, and training needs, among other resources.	✓	✓	✓	✓
National Interagency Prescribed Fire Training Center (NIPFTC)	Training	2023	National Advanced Fire and Resource Institute	National	This website contains training programs to prepare fire managers from different government agencies to conduct safe and effective prescribed burns.	✓	—	✓	—
LANDFIRE: Landscape Fire and Resource Management Planning Tools	Website	2023	USFS, DOI	National	Provides agency leaders with vegetation and wildland fire/fuel information to enable strategic fire planning.	✓	✓	✓	✓
Interagency Fuel Treatment Decision Support System	Website	2023	USFS, DOI	National	Web-based application designed to help land managers with fuel treatment planning and analysis.	✓	✓	✓	✓

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
NWCG Prescribed Fire Summary and Final Complexity Worksheet	Document	2022	NWCG	National	Helps to enable effective risk management when conducting prescribed burns.	✓	—	—	—
Colorado Pile Construction Guide	Guidebook	2015	Colorado Division of Fire Prevention and Control	Written for Colorado but much of the information is broadly applicable	This guide helps managers in the process of slash pile construction and burning.	✓	✓	—	✓
Lake States Fire Science Consortium	Website	2011	Joint Fire Science Program	Minnesota, Wisconsin, Illinois, Indiana, Michigan, Ohio, Pennsylvania, New York	This website provides information to fire managers in the states surrounding the great lakes.	✓	✓	—	✓
Grassland Management With Prescribed Fire	Document	2007	University of Nebraska Lincoln	National (grassland focused)	This document gives an overview of how to use prescribed fire for grassland management in the United States.	✓	✓	—	—

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Reduced wildfire risk:** Prescribed burns reduce hazardous fuel loads, decreasing the potential for catastrophic fires (Greco 2018). Because dense vegetation can create increasingly intense wildfires as a result of fuel connectivity, prescribed burns are a valuable tool in reducing these fuel loads in a controlled manner (Mississippi Forestry Commission n.d.).
- **Improved air quality:** Air quality is improved as a result of prescribed burns because of the reduced risk of catastrophic fire (EPA 2021). Fires release particulate matter, including hazardous PM2.5 particulates, and gaseous compounds. Prescribed fires are required to follow a smoke management program under state-specific guidelines and, if conducted properly, "the smoke exposure will not exceed air quality standards or affect sensitive populations" (Jaffe et al. 2020). In addition to generally fewer fuels being consumed in a prescribed burn as compared to a wildfire, it was found that prescribed burns resulted in less PM2.5 emissions per kilogram of fuel consumed (Lui et al. 2017).

Social and Economic

- **Public health and safety:** Prescribed burns can improve public safety and reduce public risk as a result of catastrophic wildfire reduction (Greco 2018, Avitt 2023). With many people currently living in the WUI, prescribed burns can reduce the impact of naturally occurring wildfires in these areas (Cobb 2020). The public health risk also decreases after prescribed burning as a result of less smoke and particulates in the air as compared to wildfires (Burke et al. 2020; Lui et al. 2017).
- **Property and infrastructure protection:** Prescribed burns reduce property and infrastructure damage because of decreased catastrophic wildfire potential (Warnell et al. 2020).
- **Jobs:** Expanding prescribed fire programs can create more job opportunities within the wildland fire space. With the Bipartisan Infrastructure Law (BIL) dedicating funding to wildland fire efforts, there is an opportunity to hire more professionals to work on fuel treatment projects, such as prescribed burning (Coulter 2023).
- **Firefighter safety:** Prescribed burns can create spaces for firefighters to practice fighting wildfires safely and effectively (USFS n.d.b).

Ecological

- **Native plants:** Prescribed burns can allow species dependent on fire to thrive (Greco 2018). A forest or landscape that consists of fire-dependent species will also lead to less catastrophic wildfires (Warnell et al. 2020).
- **Supports wildlife:** Prescribed burns can benefit endangered species' habitats and other wildlife (Greco 2018). Healthy forests generally allow for improved wildlife

populations. These benefits are often species-specific and targets should be specified in any prescribed burn plan (Avitt 2023).

- **Enhanced soil health:** Soil rejuvenation is an ecological benefit of prescribed burning as a result of the reduction in intense wildfires that cause excessive nutrient loss. Prescribed burns also aid in the return of nutrients from vegetation into the soil (Mississippi Forestry Commission n.d.).
- **Invasive and nuisance species management:** Prescribed fires can decrease the spread and effects of invasive species, insects, and diseases that frequently plague forests and other landscapes (USDA n.d.).
- **Improved water quality:** In many parts of the country, water quality depends on trees and organic material covering the ground adjacent to water sources such as reservoirs or streams. Because extreme wildfires can completely remove all trees, ground cover, and soil nutrients, this often leads to erosion and poor water quality (Avitt 2023).

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 prescribed burns are included here.

- **Expense:** The estimated costs of a prescribed burn range between $100 and $1,000 per acre (Burke et al. 2020). In the 2021 fiscal year, the DOI spent $220 million on fuel management; this will increase with the introduction of new legislation (DOI 2015). In the 2024 fiscal year, the DOI budget request is $1.33 billion for wildland fire and hazardous fuels mitigation (DOI 2023). The BIL and the Inflation Reduction Act will provide additional federal funding for wildfire prevention, which includes hazardous fuels management (The White House 2021, 2022). However, reacting to wildfires is much more expensive than prescribed burns or other fuel treatments—from 2011 to 2020, federal agencies spent more than $1.4 billion on fighting wildfires per year, not including the cost of property damage, loss of civilian life, or adverse effects to the ecosystem (Bishop 2023).
- **Capacity:** Many fire managers have expressed that one of the key barriers to implementing prescribed fires is the lack of capacity during burn windows. Typically, this capacity limitation refers to the lack of trained personnel (Schultz 2017).
- **Public opinion:** Prescribed burns are not always accepted by the general public, and there is valid reasoning for this distrust. It is crucial to encourage public engagement and education pertaining to fuel management. Maintaining a positive image and engaging with the public effectively and positively is essential (Brenner et al. 2014).
- **Conflict with other land uses**

- **Regulation:** Prescribed burning is heavily regulated in the United States, dating back to the US government preventing Indigenous people from conducting cultural burns (Long et al. 2021). In 2022, the USFS banned prescribed burns for a 90-day review (Moore 2022). The strict regulations on prescribed burns can lead to less burning than is deemed necessary, but being aware of the regulations in each region can allow one to take advantage of burn windows available. Restrictions on prescribed burning are site-specific and can even vary by county (Oldham 2023).
- **Lack of effectiveness data**

Economic

- **Cost of escaped fire:** The cost of an escaped prescribed burn that turns into a wildland fire can be severe. An extreme example of this is the cost of the Calf Canyon/ Hermits Peak Fire, which will end up costing federal agencies at least $3.95 billion in damages (FEMA). To combat this, it is crucial to follow the burn plan and maintain monitoring efforts (NWCG 2022). Escaped fire is rare—the USFS reported that 99.84% of their prescribed burn projects go according to plan (Moore 2022).

Community

- **Smoke/air quality:** Smoke can negatively impact communities by degrading the air quality in the area (Greco 2018). To ensure proper smoke dispersal, it is crucial to only burn within the burn window and continue monitoring smoke throughout the entire burn (NWCG 2022). Although the effects of smoke from wildfires are typically worse than prescribed burns, it is important to acknowledge the effects that particulates, specifically $PM_{2.5}$, from prescribed burns have on human health (Haikerwal 2015).
- **Threats of loss of property/life if fire escapes:** There is always a potential threat to property or lives if the prescribed burn project does escape. While this is uncommon, it is crucial to follow the burn plan and monitor effectively to ensure this does not happen and, if it does, the proper people are notified (NWCG 2022, Moore 2022).
- **Liability:** If something goes wrong or the fire escapes, federal agencies and/or the burn boss can be held liable resulting in financial, time, and mental health burdens. There are different types of liability, but the most common for prescribed burns is simple negligence liability (Berger n.d.).
- **Danger to firefighters:** Although hazard pay does not extend to prescribed burns, they can still be volatile and endanger wildland firefighters. Prescribed burns can increase the risk of disease through smoke and particulate exposure and can result in an escaped wildfire, which has further implications for firefighter danger (Grassroots Wildland Firefighters n.d.).

Ecological

- **Burn window limitations:** Not all regions that require prescribed burns have enough burn windows to properly conduct enough burning to be maximally effective. In many parts of the country, climate change is decreasing the number of burn opportunities due to atmospheric, wind, humidity, and temperature constraints (Kupfer et al. 2020).

- **Pile burning:** Burning slash piles as a means of fuel management, typically after a thinning project, can have long-term negative impacts on forest ecology, particularly on soils. If not correctly built (i.e., too large or too many heavy fuels), burning slash piles can lead to similar impacts on soil chemistry that are observed in extreme wildfires (decreased levels of total carbon and nitrogen) (Johnson 2010). Pile burning is still one of the most effective forms of fuel management, so managers using pile burning as a management method should be aware of rehabilitation efforts that are site-dependent (Mott et al. 2021).
- **Biodiversity loss:** In the Western United States, as a result of burning outside of the natural fire season, species that have adapted to fire may not be as well adapted to burns happening in fall or spring. In the Eastern United States, these same wildlife concerns are less of an issue because the prescribed burn season matches the natural fire season. To maintain biodiversity, managers can vary the timing of prescribed burns within the same region. However, it is important to note that most species are resilient to prescribed burns (Knapp et al. 2009).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Prescribed Under-burning in Southwest Oregon	Southwest Oregon	**BLM**	Cross-collaboration with federal agencies, broadcast burn with perimeter monitoring, strip-firing techniques	36	\$300 to \$700 per acre	Not provided	This project was on private land managed for both timber and ecosystem purposes. A 12-person BLM crew conducted the burn.	High-severity fires, restore ecosystem processes	The burn did reduce the potential for devastating wildfires, but there were also a series of commercial and noncommercial thinning operations performed before the burn. The burn killed some trees, which allowed for more patches in the forest, a desired outcome in this case.
Animas City Mountain Prescribed Burn	Durango, CO	**BLM**	Ignition operations that are consistent within ponderosa pine and oak brush ecosystems, establish a black line to create a secure edge and light the units back toward the black line	652	Not provided.	2 to 3	This project had a plan consisting of 21 elements. The mountain was divided into seven units to properly and safely complete the burn project.	High-severity fires, improve forest health and wildlife habitat	The project description details alternative plans in case there was too much smoke or the fire was burning too hot. They also outlined monitoring efforts.

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Lower North Fork Prescribed Fire	Conifer, CO	Colorado State Forest Service	Ignition operations, spot fire monitoring, declaring a wildfire after a prescribed burn has escaped	4,140	Total not provided($18 million was allocated from the state to the victims. [Claims Journal 2014])	12 (May 22–April 2, 2012 [NASA 2012])	This project was a well-known prescribed burn incident that led to a declared wildfire, leading to three deaths and 25 homes damaged or destroyed (NASA 2012).	Reduce fuels, high-severity wildfires.	This burn was conducted in 2012 and is an example of why prescribed burn operations must be adaptable. In this case, the weather forecast held extreme winds, and the burn did not burn as much fuel within the burn perimeter as expected, so the increased wind allowed for an escape.
Lathrop Bayou Prescribed Fire	Florida panhandle	**BLM, USFWS**	Using fire to reduce hazardous fuels, aerial ignition with limited ground support	536	Not provided	1 to 2	This project was designed to reduce severe wildfires, increase public safety, improve habitat for red-cockaded woodpeckers, and promote growth of wildflowers(BLM 2020). The reduction of hazardous fuels was necessary because the area was heavily impacted by Hurricane Michael.	Hazardous fuels, high-severity wildfires	Not provided

Bolding indicates DOI affiliates.

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