ROADMAP

Our Coasts, Resiliency, and Carbon Dioxide Removal

A Practitioner-Informed Roadmap for Enhancing Coastal Resilience and CDR Potential Along the U.S. Coastline

As the demand for resilient coastal infrastructure grows, integrating resilience projects with carbon dioxide removal (CDR) offers an opportunity to address both climate adaptation and mitigation, generating dual benefits for communities and ecosystems.

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Life of Robbie via Pexels

Contents

Glossary of Acronyms

AB
assembly bill

BCDC
San Francisco Bay Conservation and Development Commission

CAMA
Coastal Area Management Act (North Carolina)

CDP
coastal development permit

CDR
carbon dioxide removal

CEQA
California Environmental Quality Act

CNRA
California Natural Resources Agency

CPRA
Coastal Protection and Restoration Authority (Louisiana)

CSO
combined sewer overflow

CUP
Coastal Use Permit (Louisiana)

CWPPRA
Coastal Wetlands Planning, Protection and Restoration Act (Louisiana)

CWA
Clean Water Act

CZM
Coastal Zone Management

EO
executive order

EPA
Environmental Protection Agency

FPIC
free, prior, and informed consent

GI
green infrastructure

GOMESA
Gulf of Mexico Energy Security Act

Gt
gigatonne

LTCP
Long-Term Control Plan

mCDR
marine carbon dioxide removal

MRV
monitoring, reporting, and verification

MS4
municipal separate storm sewer system

NCDEQ
North Carolina Department of Environmental Quality

NEPA
National Environmental Policy Act

NJDEP
New Jersey Department of Environmental Protection

NMS
National Marine Sanctuary

NOAA
National Oceanic and Atmospheric Administration

NPDES
National Pollutant Discharge Elimination System

NWP
nationwide permit

NWL
natural and working lands

OAE
ocean alkalinity enhancement

REAL
Resilient Environments and Landscapes (New Jersey)

RESTORE Act
Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States Act

SB
senate bill

SWRCB
State Water Resources Control Board (California)

TLP
thin-layer placement

USACE
United States Army Corps of Engineers

Hilary H via Pexels

Executive summary

Dual benefits: Additional benefits (habitat, flood risk reduction, water quality, monitoring capacity) realized alongside the primary project goal.

Billion-Dollar Disaster (NOAA): A U.S. weather/climate event with damages ≥ $1 billion, used as an indicator of risk and adaptation needs.

Alkalinity: Water's capacity to neutralize acids, largely controlling ocean pH buffering; raising alkalinity generally enhances seawater CO_2 uptake.

Combined sewer overflow (CSO): Discharge events when combined sewer–stormwater systems exceed capacity during storms and release untreated/wet-weather flows.

Stormwater management (coastal): Systems that handle rainfall/runoff and tidal backflow to reduce flooding, erosion, and pollution; includes green and gray infrastructure.

The United States' coasts support major populations, economic activity, and critical ecosystems,

yet face accelerating risks from sea-level rise, erosion, flooding, and related or additional billion-dollar disasters. As the demand for resilient coastal infrastructure grows, integrating resilience projects with carbon dioxide removal (CDR) offers an opportunity to address both climate adaptation and mitigation, generating dual benefits for communities and ecosystems.

This roadmap identifies three coastal resilience pathways that offer possibility for strong technical alignment with abiotic marine CDR (mCDR):

1. Living shorelines

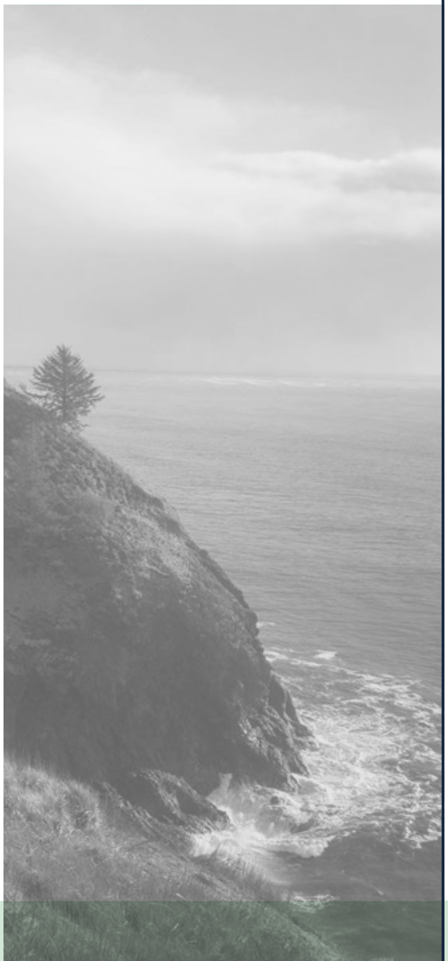
Strategically placing materials (e.g., shellbags, rocks, and dunes) can improve coastline resilience to erosion and extreme weather. Many living shoreline designs integrate sand and gravel to enhance shoreline stabilization. Including alkaline-rich sediments can remove carbon from the atmosphere and lock it away in the ocean.

2. Ecosystem restoration

Organic-rich marshes help to decrease wave energy thereby mitigating coastal flooding. They are great environments to facilitate the breakdown of carbon-absorbing material in addition to naturally generating alkalinity. In many states, the use of sediment on the marsh, herein referenced as thin-layer placement, is used in restoration projects to combat rising sea level. Alkaline material can be used in this process to enhance the amount of carbon taken up by these organic systems.

3. Stormwater management

Coastal flooding from sea level rise is compounded with increasingly large rainfall events in many coastal states. Pump stations, retention tanks, wet-weather treatment trains, existing combined sewer overflow infrastructure, and new green infrastructure all help to combat compound flooding. This infrastructure can be used to add alkaline materials to stormwater in a contained, measurable system.



Ken Cheathm via Pexels

This roadmap selects four coastal state case studies

using weighted criteria spanning policy, regulatory coordination, economic dependence on the coast, disaster exposure, and institutional capacity, **to illustrate opportunities for abiotic mCDR integrations**. Based on these assessment methods, Louisiana, California, North Carolina, and New Jersey are strong near-term candidates. We explore these four states in depth, examining plausible CDR integration points and the enabling policies, permitting pathways, and existing investments that could support early pilots.

Successful integration requires more than technical and policy feasibility. Monitoring, reporting, and verification (MRV) of CDR and ecosystem response must be established before and throughout pilot deployment and updated throughout maturation of the approach. Meaningful community and Indigenous engagement are essential for legitimacy, safety, and equitable design. This roadmap highlights opportunities for accountable CDR integrations that strengthen environmental monitoring capacity, diversify sediment supply chains, and bring new funding to coastal resilience projects.

The roadmap concludes with recommendations for policymakers, state agencies, CDR and resilience practitioners, and funders to co-develop pilots, align permitting expectations, build shared technical guidance, and institutionalize community engagement. **Embedding scientifically grounded CDR within resilience infrastructure can create durable pathways for both fields to advance: adaptation that mitigates, and mitigation that enhances resilience.**

Coastal resilience: The capacity of coastal ecosystems, economies, and communities to withstand, adapt to, and recover from coastal hazards.

Biotic mCDR: CO_2 removal pathways that rely on living organisms (e.g., seaweed cultivation and sinking or nutrient fertilization) to take up and lock away carbon from the atmosphere.

This roadmap:

- Identifies where abiotic mCDR can physically embed in existing U.S. coastal resilience solutions.
- Illustrates real-world opportunities and permitting considerations.
- Highlights near-term research priorities for integrated resilience projects
- Outlines early-stage MRV requirements and invested/Indigenous community engagement principles for responsible pilots.
- Recommends concrete next steps for policymakers, agencies, practitioners, and funders to advance the field toward implementation.

This roadmap does not:

- Provide engineering-level design specifications, dosing rates, or material standards for mCDR.
- Quantify CDR potential for specific sites or projects.
- Evaluate integration opportunities for CDR beyond abiotic methods (e.g., biotic mCDR or land-based CDR) or for all U.S. coastal states, though promising opportunities exist beyond the selected case studies.
- Provide detailed analysis of environmental review, permitting processes, or community consent requirements or official guidance.
- Present guaranteed pathways for funding CDR and coastal resilience projects.

Introduction

Carbon sequestration: The storage phase of CDR, largely referring to retaining CO_2 as organic carbon, like biomass and soils.

Beneficial use of dredged sediment: Placing dredged material to restore habitats, nourish beaches/dunes, or support resilience features, rather than disposing offshore.

Carbon dioxide removal (CDR): Activities that remove CO_2 from the atmosphere and store it for long periods (ideally ≥ 1,000 years).

Gigatonne (Gt): One billion metric tonnes; used to describe global CDR scaling needs.

The United States' coastline is foundational to the nation's economy, communities, and ecological resilience, yet many coastal regions are already degraded or vulnerable, amplifying exposure to climate-driven disasters. In the U.S., 40% of the population resides in coastal areas, generating $10 trillion in goods and services annually.[1] However, since 2018, coastal states have experienced 480 disasters which have individually resulted in more than $1 billion in damages.[1] To protect the nation's coastlines, a diverse portfolio of strategies is supported by states, municipalities, the federal government along with philanthropy and industry. These approaches are known as **coastal resilience projects; they enhance the capacity of coastal ecosystems, economies, and communities to recover quickly after experiencing coastal stress.**[2]

As coastal disasters increase in severity and frequency, efforts to improve coastal resilience are expanding. This growing scope, beyond traditional protection measures, heightens demand for capital, materials, and expertise. Dual-benefit projects are a means to solve some of these challenges. For example, the beneficial use of dredged sediment,[3] the creation of coastal organism habitat,[4] and organic carbon sequestration[5] are dual benefits of coastal resilience work that can reduce material and resource burden. **This roadmap highlights the untapped potential of integrating novel carbon mitigation, or carbon dioxide removal (CDR), as a meaningful co-benefit to coastal resilience projects.**

CDR refers to a suite of approaches that can draw down carbon dioxide (CO_2) from the atmosphere. Climate-relevant CDR requires a diverse portfolio of land- and marine-based approaches. The scale of CDR needed to limit the worst impacts of the changing climate will continue to grow without steep emission reductions. Slow action to mitigate emissions requires at least 4.8 billion tonnes (gigatonnes) of CDR per year by 2035[6] or around 500 gigatonnes of CDR from 2020 until 2100.[7] For context, as of 2024, about 2 gigatonnes of CDR is currently taking place, but only 0.1% of this is the "novel" CDR methods that will grow global CDR capacity.[8] While compliance carbon markets remain a long-term driver to scale CDR, political factors make widespread adoption in the United States unlikely. Additionally, market forces alone may not be able to stimulate enough demand.[9] **Leveraging existing industries for CDR can build confidence, accelerate innovation, reduce costs, and serve as a positive signal to investors and philanthropy.**

1. Coast States. NOAA Office for Coastal Management https://coast.noaa.gov/states.
2. Masselink, G. & Lazarus, E. D. Defining Coastal Resilience. Water 11, 2587 https://www.mdpi.com/2073-4441/11/12/2587 (2019).
3. Mohan, R. & Herrington, T. Coastal Resiliency Considerations for America's Four Coasts: Preparing for 2100. J. Mar. Environ. Eng. 10, (2021) Bridges, T. S. et al. Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience. https://www.oldcitypublishing.com/journals/jmee-home/jmee-issue-contents/jmee-volume-10-number-4-2021/jmee-10-4-p-319-330/ (2015).
4. Davis, J. L., Currin, C. A., O'Brien, C., Raffenburg, C. & Davis, A. Living Shorelines: Coastal Resilience. https://usace.contentdm.oclc.org/digital/collection/p266001coll1/id/3442/ (2015).
5. Resilience with a Blue Carbon Benefit. PLOS ONE 10, e0142595 https://doi.org/10.1371/journal.pone.0142595 (2015).
6. Smith, S. et al. State of Carbon Dioxide Removal - 1st Edition. https://doi.org/10.17605/OSF.IO/W3B4Z.
7. AR6 Synthesis Report: Climate Change 2023. https://www.ipcc.ch/report/ar6/syr/.
8. Smith, S. et al. The State of Carbon Dioxide Removal - 2nd Edition. https://doi.org/10.17605/OSF.IO/F85QJ (2024).
9. What Does the Future of Durable CDR Hold? https://web-assets.bcg.com/15/ca/ebf8d43f42bba0ec028b1c826fe8/what-does-the-future-of-durable-cdr-hold-june-2024.pdf (2024).

Within this broader CDR portfolio, we group mCDR approaches into two categories, biotic and abiotic, based on the processes they leverage to remove carbon. This roadmap focuses on abiotic pathways, which leverage the geologic carbon cycle to lock carbon away from the atmosphere for over a thousand years.[10,11] These approaches have gigatonne-scale potential globally[12] but remain early stage and in need of in-field projects for further development.[13] Open-system approaches like mCDR face significant monitoring, reporting, and verification (MRV), regulatory, and public-engagement considerations; embedding them within sectors that already have established economic returns, regulatory drivers, and public investment mechanisms can improve uptake and long-term viability. Specifically, such projects will be valuable for researchers to gather data, to iterate on regulatory pathways, and for practitioners to engage communities on the ground.

Coastal resilience projects provide an ideal proving ground for abiotic mCDR integration as they align public investment, community priorities, and measurable environmental benefits. As abiotic mCDR approaches progress from laboratory studies to carefully monitored field studies, resilience projects offer a practical pathway for pilot-scale demonstrations across varied coastal environments. Embedding CDR into these efforts can strengthen MRV, build public trust through community co-design, and accelerate market and policy maturity. Coastal resilience demand combined with growing municipal interest in CDR (as illustrated by the City CDR Initiative) presents a timely opportunity to integrate CDR into coastal resilience planning and implementation.

This roadmap draws on research and insights from more than 40 interviews to produce a practitioner-informed strategy to include CDR in U.S. coastal resilience infrastructure. It builds from the premise that integrating CDR into coastal resilience pathways at this moment has dual benefit to both fields. **Coastal resilience and CDR strategies both address urgent climate challenges; one adapts to impacts, the other mitigates them.** Embedding CDR into coastal resilience projects can deliver a range of ecological, social, and economic benefits while leveraging overlapping monitoring systems, funding channels, and policy frameworks.

Monitoring, reporting, and verification (MRV): The set of measurements, documentation, and third-party checks used to quantify and validate CO_2 removal and assess impacts.

Open-system approach: The use of diffuse environments to draw down carbon dioxide from the atmosphere. These stand in contrast to approaches that utilize contained systems where CDR can be measured in that same system. These approaches include CDR that happens in open fields, rivers, coasts and the ocean.

Practitioner-informed: Refers to an approach, plan, or framework that is grounded in the real-world experience, insights, and day-to-day practices of individuals directly engaged in the field. In the case of this roadmap, the practitioners operate in the coastal resilience field.

[10] Renforth, P. & Henderson, G. Assessing ocean alkalinity for carbon sequestration. Rev. Geophys. 55, 636–674 https://doi.org/10.1002/2016RG000533 (2017).
[11] Middelburg, J. J., Soetaert, K. & Hagens, M. Ocean Alkalinity, Buffering and Biogeochemical Processes. Rev. Geophys. 58, e2019RG000681 https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019RG000681 (2020).
[12] Cross, J. N. et al. Strategy for NOAA Carbon Dioxide Removal Research: A White Paper Documenting a Potential NOAA CDR Science Strategy as an Element of NOAA's Climate Interventions Portfolio. https://sciencecouncil.noaa.gov/cdr-strategy/ (2023).
[13] National Academies of Sciences, Engineering, and Medicine. A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration. https://doi.org/10.17226/26278 (2022).

Abiotic mCDR

This roadmap focuses on abiotic mCDR approaches, which enhance the ocean's capacity for atmospheric CO_2 uptake by increasing alkalinity. This CO_2 uptake is governed by a set of reactions (Equations 1 and 2), known as carbonate system chemical equilibria,[14] that describe how CO_2 (a weak acid) interacts with ocean water.

Abiotic mCDR: Approaches that rely on chemical/physical processes (e.g., alkalinity addition, direct ocean capture) to draw down CO_2.

Marine CDR (mCDR): CDR approaches within rivers, coasts, or the ocean (see biotic and abiotic).

Living shoreline: Nature-based shoreline stabilization using plants, marsh benches, oyster reefs, coir logs, and light rock to reduce erosion while maintaining habitat.

Ecosystem restoration (coastal): Re-establishing or enhancing marshes, seagrasses, mangroves, ridges, and hydrology to improve resilience and services.

Equation 1

$$CO_{2\,(aq)} + H_2O \longrightarrow HCO_3 + H^+$$

Equation 2

$$HCO_3^- \longrightarrow CO_3^{2-} + H^+$$

Dissolved CO_2 reacts with water to form carbonic acid, which quickly forms bicarbonate (HCO_3^-; Equation 1) and carbonate (CO_3^{2-}; Equation 2) ions.[14,15] Bicarbonate ions are the most abundant form of carbon in the ocean[14] and are stable for at least 1000 years.[11] Total alkalinity reflects seawater's capacity to neutralize acidity (e.g., CO_2) and stabilize bicarbonate and carbonate in the ocean.[11,13] Increasing alkalinity drives the conversion of CO_2 in surface water to bicarbonate and carbonate ions, increasing the surface ocean's capacity to dissolve more CO_2 from the atmosphere.[16]

There are two main ways to add alkalinity to coastal systems to enable abiotic mCDR, by mineral or aqueous addition. For this roadmap, integrations into living shorelines, ecosystem restoration, and stormwater management are focused on mineral addition, while aqueous addition could also be used in stormwater integrations. This section provides a general comparison of efficacy and high-level details on lifecycle emissions considerations for these approaches.

[14] Zeebe, R. E. & Wolf-Gladrow, D. CO_2 in Seawater: Equilibrium, Kinetics, Isotopes. (Gulf Professional Publishing, 2001).
[15] Dickson, A. G. The carbon dioxide system in seawater: equilibrium chemistry and measurements. Guide Best Pract. Ocean Acidif. Res. Data Report. 1, 17–40 (2010).
[16] Doney, S. C., Fabry, V. J., Feely, R. A. & Kleypas, J. A. Ocean acidification: the other CO2 problem. Annu. Rev. Mar. Sci. 1, 169–192, https://doi.org/10.1146/annurev.marine.010908.163834 (2009).

Alkalinity addition

Abiotic mCDR can be pursued by the addition of mineral- or aqueous-based alkalinity,* which both leverage the carbonate chemistry for CO_2 uptake. For mineral addition, we focus on two main types of naturally occurring minerals for this coastal placement: silicate and carbonate minerals. (Manufactured sources of mineral alkalinity, e.g., waste slag and quicklime, are not considered in this roadmap.) For aqueous addition, we focus on the addition of manufactured alkalinity, NaOH.

Silicate minerals such as olivine (forsterite), wollastonite, and anorthite dissolve to release cations (e.g., Mg^{2+}, Ca^{2+}) and alkalinity. Olivine has received the most attention due to its abundance and high CO_2 drawdown potential, with studies estimating ~0.5–1.0 tonnes of CO_2 removed per tonne applied after accounting for project emissions.[17–19] Efficacy depends on mineral composition and dissolution rates, which vary with local biogeochemical conditions and mineral surface area.[19,20] To increase surface area, minerals are commonly ground to micro- to millimeter scales, increasing lifecycle energy demand from grinding in addition to mining and transport emissions.[21,22]

Carbonate minerals, particularly limestone ($CaCO_3$), can also dissolve to release cations and alkalinity. Because calcium carbonate already contains carbon, its CO_2 removal efficacy is lower than that of silicate minerals, with approximately 0.3 tonnes of CO_2 removed per tonne of $CaCO_3$ applied.[21] Most coastal waters are supersaturated with respect to $CaCO_3$; therefore dissolution generally requires elevated CO_2 or low pH conditions, which occur in some coastal systems.[23] Under these conditions, $CaCO_3$ is more likely to neutralize CO_2 and reduce outgassing rather than increase atmospheric uptake, which is a form of mCDR,[24] and may simplify MRV. Limestone is widely available and often locally sourced,[25] reducing lifecycle emissions, and has a long history of use in coastal protection (e.g., riprap), suggesting low ecological risk when added to coastal environments.[26]

Compared to mineral addition, aqueous NaOH has the advantages of allowing for precise control over alkalinity delivery rates and location.[13] This addition has the theoretical chemical efficacy of 0.84 moles of CO_2 per mole of alkalinity added,[27] with the realized efficacy dependent on local conditions affecting how long it takes for CO_2 in the atmosphere and surface ocean to equilibrate compared to time the alkaline-rich water spends in the surface ocean.[28] However, this approach must also account for their often high energy requirements, and management of acid by-products during manufacturing to ensure net CO2 removal.[13,29]

** There are a few terms used to describe alkalinity-based CDR. Other terms used in this report include enhanced weathering (when alkalinity is placed on land) and ocean alkalinity enhancement (when alkalinity is added to water).

17 Moosdorf, N., Renforth, P. & Hartmann, J. Carbon Dioxide Efficiency of Terrestrial Enhanced Weathering. Environ. Sci. Technol. 48, 4809–4816, https://doi.org//10.1021/es4052022 (2014).

18 Renforth, P. The potential of enhanced weathering in the UK. Int. J. Greenh. Gas Control 10, 229–243, https://doi.org/10.1016/j.ijggc.2012.06.011 (2012).

19 Geerts, L. J. J., Hylén, A. & Meysman, F. J. R. The CDR potential of olivine-based enhanced rock weathering in marine systems: a case study for the coastal zone of France. Environ. Res. Lett. 20, 074049, https://doi.org/10.1088/1748-9326/addf60 (2025).

20 Meysman, F. J. R. & Montserrat, F. Negative CO2 emissions via enhanced silicate weathering in coastal environments. Biol. Lett. 13, https://doi.org/10.1098/rsbl.2016.0905 (2017).

21 Eisaman, M. D. et al. Assessing the technical aspects of ocean-alkalinity-enhancement approaches. Guide Best Pract. Ocean Alkalinity Enhanc. Res. 2-oae2023, 3, https://doi.org/10.5194/sp-2-oae2023-3-2023 (2023).

22 Foteinis, S., Campbell, J. S. & Renforth, P. Life Cycle Assessment of Coastal Enhanced Weathering for Carbon Dioxide Removal from Air. Environ. Sci. Technol. 57, 6169–6178, https://doi.org/10.1021/acs.est.2c08633 (2023).

23 Lee, C.-H., Subhas, A. V., Kim, J.-H. & Lee, K. Ocean Carbon Dioxide Removal and Storage. Chem. Rev. 126, 1110–1144, https://doi.org/10.1021/acs.chemrev.5c00433 (2026).

24 Oschlies, A. et al. Climate targets, carbon dioxide removal, and the potential role of ocean alkalinity enhancement. Guide Best Pract. Ocean Alkalinity Enhanc. Res. 2-oae2023, 1, https://doi.org/10.5194/sp-2-oae2023-1-2023 (2023).

25 Caserini, S., Storni, N. & Grosso, M. The Availability of Limestone and Other Raw Materials for Ocean Alkalinity Enhancement. Glob. Biogeochem. Cycles 36, https://doi.org/10.1029/2021GB007246 (2022).

26 Bowles, O. & Jensen, N. C. Industrial Uses of Limestone and Dolomite. (U.S. Bureau of Mines, 1947).

27 Schulz, K. G., Bach, L. T. & Dickson, A. G. Seawater carbonate system considerations for ocean alkalinity enhancement research. (2023). https://doi.org/10.5194/sp-2023-12.

28 Zhou, M. et al. Mapping the global variation in the efficiency of ocean alkalinity enhancement for carbon dioxide removal. Nat. Clim. Change 15, 59–65, https://doi.org/10.1038/s41558-024-02179-9 (2025).

29 Eisaman, M. D. et al. Indirect ocean capture of atmospheric CO2: Part II. Understanding the cost of negative emissions. Int. J. Greenh. Gas Control 70, 254–261, https://doi.org/10.1016/j.ijggc.2018.02.020 (2018).

Abiotic mCDR as a co-benefit to resilience

Embedding abiotic mCDR into coastal resilience projects creates a practical pathway for innovation within a sector that is often constrained by tight budgets, short funding cycles, and limited resources for monitoring and research. Coastal resilience practitioners already manage complex permitting, infrastructure deployment, and long-term stewardship in dynamic coastal environments, capabilities that closely align with the operational needs of mCDR projects. By integrating mCDR as a co-benefit of resilience infrastructure, coastal practitioners can leverage emerging research, philanthropic, and public funding streams to support enhanced monitoring, data collection, and iterative design in projects that may otherwise struggle to fund these activities. Furthermore, **integrating mCDR as a co-benefit of resilience infrastructure allows practitioners to extend the value of publicly funded adaptation projects while supporting standardized monitoring of coastal projects and improving carbon accounting in the climate and mCDR fields**. Although the chemical basis for abiotic mCDR is well established, uncertainties remain particularly around monitoring of carbon and ecosystem impacts in complex coastal ecosystems.[13,30] Integrated coastal resilience mCDR projects therefore embed innovation, learning, and community oversight into infrastructure designed for public benefit and long-term climate risk management.

Carbon accounting: Quantifying CO_2 removed (and related emissions/impacts) using standardized methods as part of MRV.

[30] Doney, S. C., Wolfe, W. H., McKee, D. C. & Fuhrman, J. G. The Science, Engineering, and Validation of Marine Carbon Dioxide Removal and Storage. Annu. Rev. Mar. Sci. (2025). https://doi.org/10.1146/annurev-marine-040523-014702.

Coastal resilience integrations

The three coastal resilience pathways discussed in this roadmap are highlighted because they provide resilience benefits to a community against coastal hazards like sea level rise, erosion, and storm surges as well as the means to execute abiotic mCDR. Coastal protection mechanisms (e.g., seawalls and bulkheads) that would require new hardened coastal infrastructure are not examined in this roadmap. Similarly, coastal projects that are largely for tourism and recreational benefits (e.g., beach nourishment for the purpose of beach widening) are also not considered here, although the process remains relevant to some of the integration mechanisms. **The pathways described include living shorelines and ecosystem recovery, which allow for delivery of mineral-based alkalinity, and stormwater management systems, which allow for both mineral- and aqueous-based alkalinity addition**. These pathways are first defined and contextualized in their coastal resilience function then examined for their integration opportunities.

Living Shorelines

Resilience function

A living shoreline is a nature-based shoreline stabilization approach that reinforces the land–water interface and reduces erosion. We further define living shorelines as features that combine structural elements like oyster reefs and low rocks sills, or designed elements, with plants and other natural elements. These structures are meant to reduce the reliance on other shoreline stabilization methods, such as traditional seawalls and bulkheads, that may have negative effects on sediment transport and marine life.[31] Living shorelines are best suited for lower-energy environments such as bays, estuaries, and tidal tributaries,[32,33] however dune and bluff management can serve as living shorelines for open-ocean systems.[34]

Many of these resilience structures utilize materials native to the location at hand, including rocks and shell-based material to create a wave break structure, which is usually backfilled with native vegetation and tidal marsh sods. Materials can also be imported to supplement these structures, including mineral and aggregate elements for low rock sills, cobble and gravel for cobble berms, and sand fill for marsh benches and beach dune tie-ins (Figure 1). Sand and sediment is often used in living shorelines to help prepare the system for the living shoreline placement, or to help place living shoreline structures (e.g., oyster bags) in tidal settings. The exact materials used for a living shoreline will depend on the amount of wave energy, variation in high and low tides, and the slope of the shoreline.[32]

Dune: Wind-built sand ridges along coasts; berms are engineered dune features for flood/erosion protection.

Tidal marsh/meadow: Vegetated intertidal habitat providing wave attenuation, carbon storage, and alkalinity generation/export.

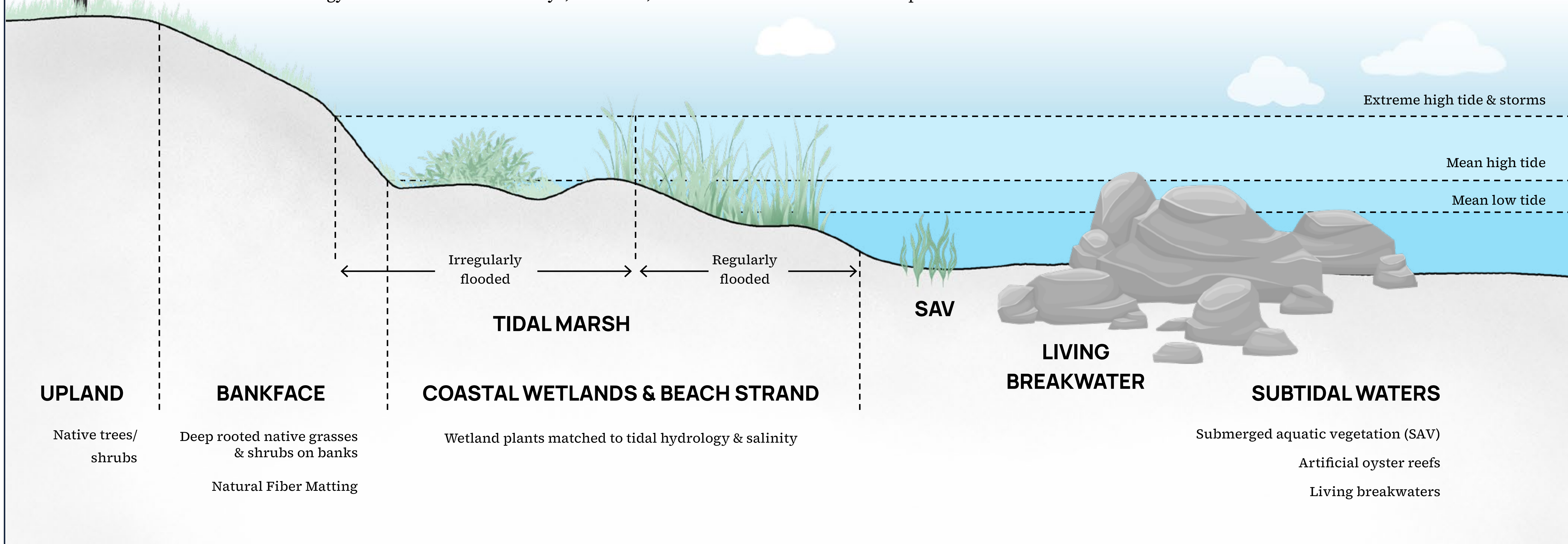


Figure 1: Graphic representation of a hybrid living shoreline solution in which a natural rock structure functions as a wave break, with marsh vegetation planted landward of the breakwater feature. Living shorelines can take various forms, including dune-based systems. Figure adapted from the Texas General Land Office.

31 Prosser, D. J. et al. Impacts of Coastal Land Use and Shoreline Armoring on Estuarine Ecosystems: an Introduction to a Special Issue. Estuaries Coasts 41, 2–18, https://doi.org/10.1007/s12237-017-0331-1 (2018).
32 Guidance for Considering the Use of Living Shorelines. (2015). https://www.habitatblueprint.noaa.gov/wp-content/uploads/2018/01/NOAA-Guidance-for-Considering-the-Use-of-Living-Shorelines_2015.pdf
33 Nunez, K., Rudnicky, T., Mason, P., Tombleson, C. & Berman, M. A geospatial modeling approach to assess site suitability of living shorelines and emphasize best shoreline management practices. Ecol. Eng. 179, 106617, https://doi.org/10.1016/j.ecoleng.2022.106617 (2022).
34 Griggs, G. B. The California Coast and Living Shorelines—A Critical Look. J. Mar. Sci. Eng. 12, https://doi.org/10.3390/jmse12020199 (2024).

Coastal resilience integrations

Hybrid: Combined nature-based and structural elements (e.g., marsh sills with rock and planted marsh) for stability and habitat.

Living shorelines are now widely implemented across the United States; over the past three decades, the National Oceanic and Atmospheric Administration (NOAA) has implemented over 200 living shorelines (Figure 2), predominantly along the Southeast and Northeast coasts. Living shoreline projects are inherently site specific, therefore their timelines and maintenance needs vary widely with design complexity, particularly hybrid systems incorporating hard structural elements driving longer permitting and construction periods.[35,36] While these systems are valued for their maintainability and adaptive capacity through repair and modification over time, most installations remain relatively young, leaving uncertainty about long-term maintenance impacts on performance, although available evidence from early projects suggests durability over at least a decade.[36,37]

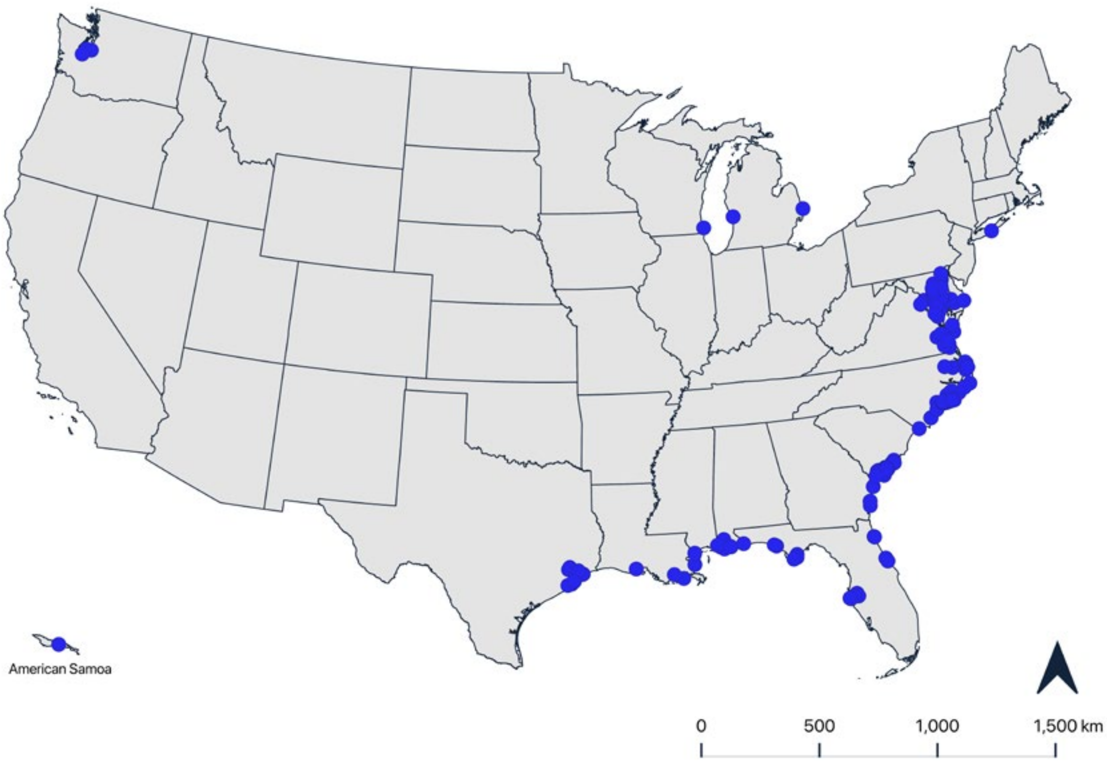


Figure 2: Location of NOAA-funded Living Shorelines projects (n = 208). Adapted from NOAA.

[35] Currin, C. Living Shorelines for Coastal Resilience. in 1023–1053 (2019). https://doi.org/10.1016/B978-0-444-63893-9.00030-7.
[36] Smith, C. S. et al. Coming to Terms With Living Shorelines: A Scoping Review of Novel Restoration Strategies for Shoreline Protection. Front. Mar. Sci. 7, https://doi.org/10.3389/fmars.2020.00434 (2020).
[37] Palinkas, C. M., Bolton, M. C. & Staver, L. W. Long-term performance and impacts of living shorelines in mesohaline Chesapeake Bay. Ecol. Eng. 190, 106944, https://doi.org/10.1016/j.ecoleng.2023.106944 (2023).

Abiotic mCDR integration

Living shorelines present a natural integration point for mineral-based abiotic mCDR, particularly through the placement of alkalinity-generating materials within shoreline stabilization structures. In order to determine the full potential of this integration, more data is needed on the amount of sand and sediment used in living shoreline projects. Research from this roadmap indicates that these parameters are not commonly disclosed within permit applications and project design. However, it is qualitatively recognized from project overviews that many **living shoreline designs incorporate rocks, shell, and aggregate materials, creating opportunities to substitute or supplement conventional materials with alkalinity-generating silicate or carbonate minerals without fundamentally altering the resilience function of the project.** The type of mineral used for abiotic CDR will be dependent on local biogeochemical factors such as temperature, salinity, and pH of the system as well as operational factors like feedstock availability.

From an implementation perspective, integrating abiotic mCDR into living shorelines aligns well with existing construction timelines, maintenance cycles, and permitting processes. Because these projects already involve material sourcing, heavy machinery, and long-term stewardship, they offer an opportunity to embed alkalinity enhancement within established coastal management practices while improving lifecycle carbon accounting. However, quantifying the associated abiotic mCDR carbon benefits would require robust monitoring of the system (see Towards implementation section).

Ecosystem restoration

Resilience function

Ecosystem restoration refers to the re-establishment or enhancement of vegetated coastal habitats, such as tidal marshes, mangroves, seagrass meadows, and dune ecosystems. The systems aim to dampen wave energy, and build elevation through both organic soil and mineral sediment accumulation (Figure 3). In doing so, they can prevent erosion and reduce tidal energy while delivering co-benefits such as improved water quality, biodiversity, and organic carbon sequestration (e.g., blue carbon).[38–41] Restoration and creation often intersect with living shorelines. In many cases, living shorelines are constructed seaward of restoration sites to further reduce wave energy and tidal forcing and serve to enhance the long-term stability of the restored system.[32,42] This is because vegetation alone is generally insufficient to protect against storm surge of sustained wave energy, particularly with rising sea levels.[43,44] As a result, restoration and creation projects typically incorporate sediment placement, elevation building, and hydrologic modifications to ensure durability.

Blue carbon: Carbon captured and stored in coastal vegetated habitats (salt marshes, mangroves, seagrass) via organic matter accumulation.

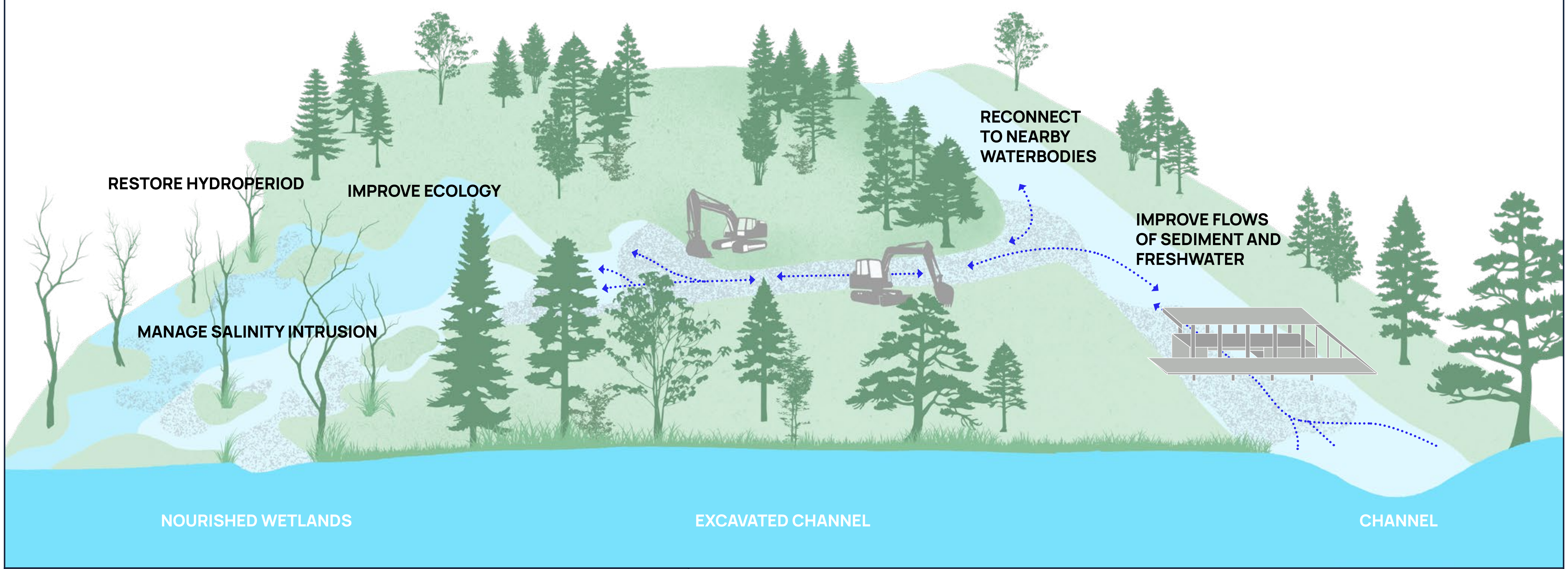


Figure 3: Example of an ecosystem restoration project that reestablished tidal gradients to enhance freshwater flow and used sediment material to increase elevation within the marsh system (TLP). Figure adapted from the 2023 Louisiana Coastal Master Plan.

[38] Barbier, E. B. et al. The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81, 169–193, https://doi.org/10.1890/10-1510.1 (2011).
[39] Shepard, C. C., Crain, C. M. & Beck, M. W. The Protective Role of Coastal Marshes: A Systematic Review and Meta-analysis. PLOS ONE 6, e27374, https://doi.org/10.1371/journal.pone.0027374 (2011).
[40] Morris, J. T. et al. Contributions of organic and inorganic matter to sediment volume and accretion in tidal wetlands at steady state. Earths Future 4, 110–121, https://doi.org/10.1002/2015EF000334 (2016).
[41] Mcleod, E. et al. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. Front. Ecol. Environ. 9, 552–560, https://doi.org/10.1890/110004 (2011).
[42] Bilkovic, D. M., Mitchell, M., Mason, P. & Duhring, K. The Role of Living Shorelines as Estuarine Habitat Conservation Strategies. Coast. Manag. 44, 161–174, https://doi.org/10.1080/08920753.2016.1160201 (2016).
[43] Vozzo, M. L. et al. Achieving at-scale seascape restoration by optimising cross-habitat facilitative processes. Npj Ocean Sustain. 3, 57, https://doi.org/10.1038/s44183-024-00095-1 (2024).
[44] Gaskin, T. A. et al. Living shoreline in USACE projects: a review. https://hdl.handle.net/11681/49678 (2025). U.S. Army Corps of Engineers.

Coastal resilience integrations

Hydrologic reconnection: Restoring water flows (e.g., breaches, culvert upgrades, diversions) to revive wetland processes and sediment delivery.

Levee/sill (living shorelines): Low-crested structures parallel to shore (sills) or higher flood barriers (levees) that attenuate waves and retain sediments.

Thin-layer placement (TLP): Spreading a thin layer of sediment over wetlands to raise elevation, maintain vegetation, and keep pace with sea level rise.

Restoration methods are highly site dependent and vary by geomorphic setting and management objectives. Common approaches include hydrologic reconnection, native vegetation planting, invasive species removal, regrading, and sediment addition. One sediment-based method has been piloted at restoration sites. Thin-layer placement (TLP), which involves applying a relatively small thickness of sediment, often sourced from dredging operations, to existing marsh surfaces to increase elevation and resilience.[45] TLP projects span the United States (Figure 4). It is important to note that TLP represents only one pathway for sediment augmentation. Other restoration approaches include nearshore sediment placement, water-column sediment seeding, and the conversion of diked or subsided baylands to tidal marsh by raising elevations to marsh level (or just below) and breaching levees to restore tidal exchange.[46,47] In some regions experiencing unprecedented rates of erosion and subsidence, states are increasingly pursuing the creation of entirely new coastal ecosystems, rather than restoration of degraded remnants.[48]

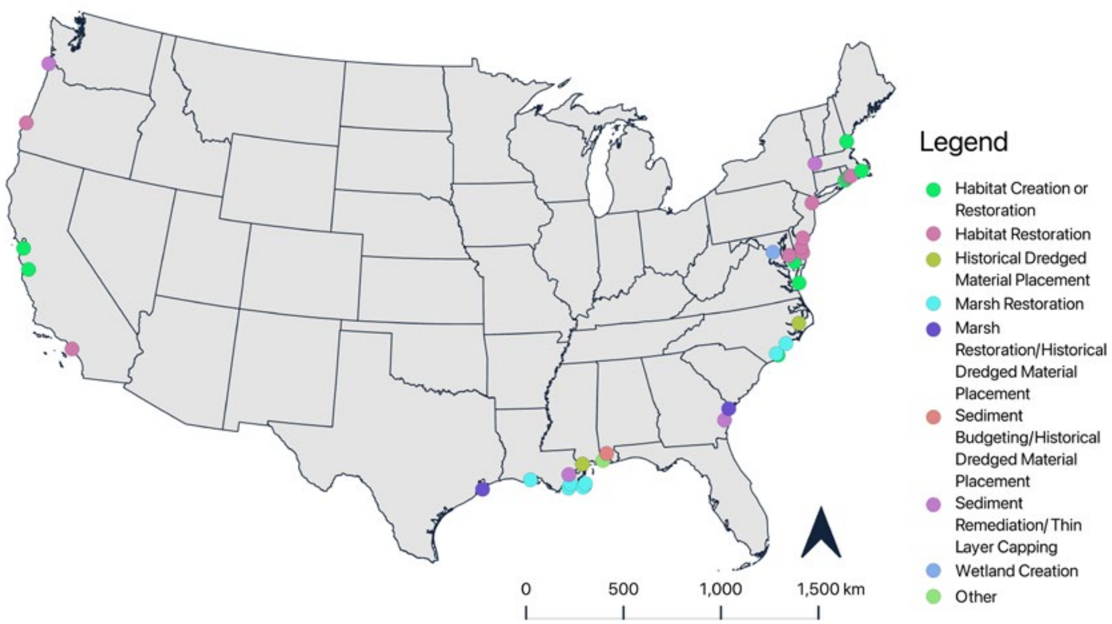


Figure 4: Thin-layer-placement case studies in marsh ecosystems reproduced from The U.S. Army Corps of Engineers (USACE) TLP map portal. USACE records note that TLP pilots have been occurring since 1978.

Project timelines for ecosystem restoration and creation vary widely with project scale, permitting complexity, sediment sourcing, and construction methods; although permitting can be lengthy, the

[45] Ray, G. L. Thin Layer Placement of Dredged Material on Coastal Wetlands: A Review of the Technical and Scientific Literature. (2007). https://apps.dtic.mil/sti/pdfs/ADA475811.pdf
[46] Williams, P. B. & Orr, M. K. Physical Evolution of Restored Breached Levee Salt Marshes in the San Francisco Bay Estuary. Restor. Ecol. 10, 527–542, https://doi.org/10.1046/j.1526-100X.2002.02031.x (2002).
[47] San Francisco Estuary Institute, (SFEI). San Francisco Bay Shoreline Adaptation Atlas: Working with Nature to Plan for Sea Level Rise Using Operational Landscape Units, (2018). https://www.spur.org/sites/default/files/2019-05/SPUR_SFEI_SF_Bay%20_Shoreline_Adaptation_Atlas.pdf

regulatory process is well established because sediment placement, heavy equipment use, and long-term monitoring are standard components of these projects. Construction can span months to multiple years, particularly for large-scale efforts involving sediment placement or hydrologic reconnection, and is typically followed by multi-year, and sometimes decade-long, monitoring to evaluate vegetation establishment, elevation change, sediment stability, and ecosystem function as restored systems mature and stabilize.[48–52]

Abiotic mCDR integration

Restored and created coastal ecosystems present a strong opportunity for integration of mineral-based abiotic mCDR. Organic-rich coastal ecosystems are often characterized by low pH sediment and porewater conditions, driven by high rates of organic matter decomposition and microbial respiration.[53,54] Under these conditions, **coastal wetlands are natural chemical reactors that can accelerate the dissolution of alkaline sediments** placed via TLP or other fill. In a field that already boasts robust monitoring practices, the advantage of this integration lies in the diversification of sediment sources, which can be particularly beneficial in sediment-limited areas. Given feedstock availability[25] and large coastal wetland coverage, this mineral-based pathway has a large scaling potential, though small-scale integrations are needed to answer critical research questions first. For example, the natural acidity of wetland systems drives known ecosystem services, such as metal and pollutant immobilization.[55] Addition of alkaline materials may change the acidity of the systems and could interact with these chemistry-dependent services. To date, there is only one known study researching this mineral-addition concept in wetlands. Early pilot projects should develop monitoring programs to best quantify these potential tradeoffs.

Even without the addition of alkaline minerals, organic-rich coastal systems naturally produce alkalinity through microbially mediated processes.[56–58] This natural alkalinity flux has been studied across the U.S.[58–62] but these fluxes have not been quantified for the purpose of CDR. Given the high rates of metabolic respiration in these coastal ecosystems, it is likely that these abiotic mCDR interventions would reduce outgassing from the coastal ecosystem rather than increase uptake, which will help inform MRV for the system.

49 Taddeo, S. & Dronova, I. Landscape metrics of post-restoration vegetation dynamics in wetland ecosystems. Landsc. Ecol. 35, 275–292, https://doi.org/10.1007/s10980-019-00946-0 (2020).
50 Janousek, C. & Williams, T. Tidal wetland restoration monitoring plan for the central Oregon coast. Prepared for Midcoast Watersheds Council by Oregon State University, (2024). https://midcoastwatersheds.squarespace.com/s/Janousek-Williams-Cen-OR-mon-plan-2024_11.pdf
51 Newling, C. J. & Landin, M. C. Wetland Creation and Restoration: The Status of the Science. (1985). https://www.nawm.org/pdf_lib/wetland_creation_restoration_vol_1.pdf
52 Monitoring the Effects of Coastal Wetland Restoration on Fish and Invertebrates Monitoring and Adaptive Management Activity Implementation Plan. (2022). https://www.gulfspillrestoration.noaa.gov/media/document/2022-07-la-4-monitoring-effects-coastal-wetland-restoration-fish-and-inverebratespdf
53 Middelburg, J. J., Vlug, T., Jaco, F. & Van der Nat, W. A. Organic matter mineralization in marine systems. Glob. Planet. Change 8, 47–58, https://doi.org/10.1016/0921-8181(93)90062-S (1993).
54 Burdige, D. J. Geochemistry of Marine Sediments. 1–624 (2020).
55 Dietrich, M. et al. Anthropogenic Metal Storage in Wetland Soils Across the Conterminous United States. Wetlands 45, 64, https://doi.org/10.1007/s13157-025-01946-4 (2025).
56 Alongi, D. M. Lateral Export and Sources of Subsurface Dissolved Carbon and Alkalinity in Mangroves: Revising the Blue Carbon Budget. J. Mar. Sci. Eng. 10, 1916, https://doi.org/10.3390/jmse10121916 (2022).
57 Fakhraee, M., Planavsky, N. J. & Reinhard, C. T. Ocean alkalinity enhancement through restoration of blue carbon ecosystems. Nat. Sustain. 6, 1087–1094, https://doi.org/10.1038/s41893-023-01128-2 (2023).
58 Wang, Z. A., Kroeger, K. D., Ganju, N. K., Gonneea, M. E. & Chu, S. N. Intertidal salt marshes as an important source of inorganic carbon to the coastal ocean. Limnol. Oceanogr. 61, 1916–1931, https://doi.org/10.1002/lno.10347 (2016).
59 ßWang, Z. A. & Cai, W.-J. Carbon dioxide degassing and inorganic carbon export from a marsh-dominated estuary (the Duplin River): A marsh CO2 pump. Limnol. Oceanogr. 49, 341–354, https://doi.org/10.4319/lo.2004.49.2.0341 (2004).
60 Song, S. et al. An important biogeochemical link between organic and inorganic carbon cycling: Effects of organic alkalinity on carbonate chemistry in coastal waters influenced by intertidal salt marshes. Geochim. Cosmochim. Acta 275, 123–139, https://doi.org/10.1016/j.gca.2020.02.013 (2020).
61 He, S. et al. Porewater chemistry of Louisiana marshes with contrasting salinities and its implications for coastal acidification. Estuar. Coast. Shelf Sci. 268, 107801, https://doi.org/10.1016/j.ecss.2022.107801 (2022).
62 Reithmaier, G. M. S. et al. Carbonate chemistry and carbon sequestration driven by inorganic carbon outwelling from mangroves and saltmarshes. Nat. Commun. 14, 8196, https://doi.org/10.1038/s41467-023-44037-w (2023).

Stormwater management

Resilience function

Stormwater management for coastal resilience refers to the planning, design, and implementation of systems that manage rainfall, runoff, and tidal or surge-driven inflows in low-lying coastal watersheds to reduce flooding, erosion, and water quality impacts. In coastal settings, stormwater systems play a critical role in reducing compound flooding risks, where intense precipitation coincides with elevated sea levels, tides, or storm surge, overwhelming drainage capacity and increasing flood impacts. As sea levels rise (Figure 5), compound flooding risks will also increase. Beyond flooding, stormwater runoff has a profound influence on coastal water quality, transporting nutrients, sediments, metals, and organic matter from urban and agricultural landscapes into estuaries and nearshore waters.[63,64] Effective stormwater management therefore serves the dual resilience objectives of protecting communities and infrastructure from flooding while reducing pollutant loading to coastal ecosystems.

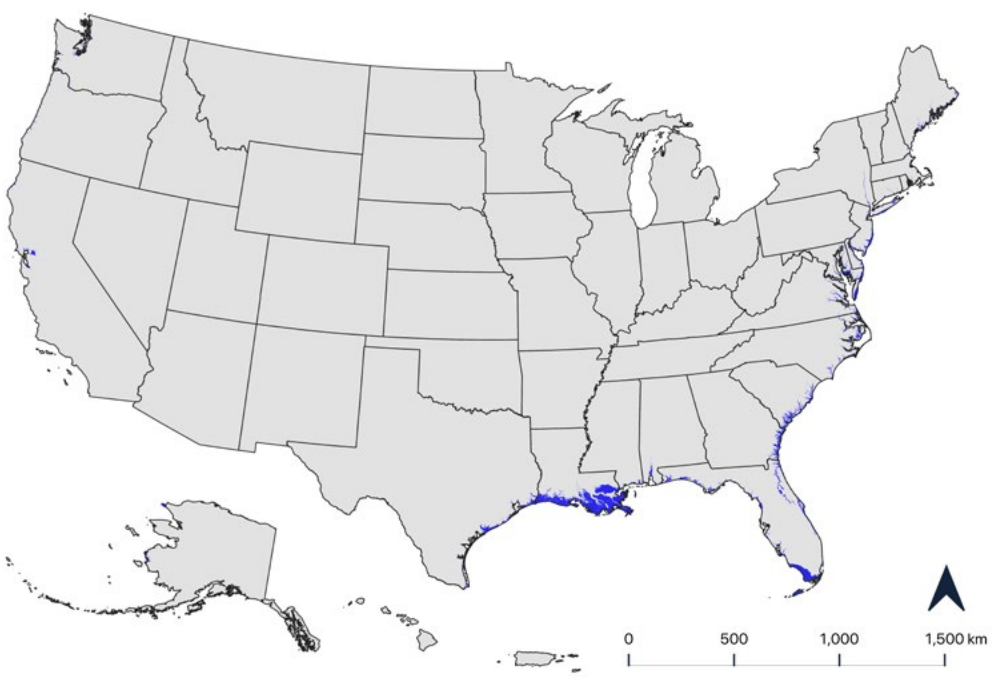


Figure 5: Estimated horizontal inundation from 1.5 feet of sea level rise (NOAA), approximately equal to changes anticipated by the Intergovernmental Panel on Climate Change Sixth Assessment Report shared socioeconomic pathway 1–2.6, which keeps temperatures at approximately +2˚C compared to preindustrial levels.[65]

[63] Paul, M. J. & Meyer, J. L. Streams in the Urban Landscape. Annu. Rev. Ecol. Syst. 32, 333–365, https://doi.org/10.1146/annurev.ecolsys.32.081501.114040 (2001).
[64] Tsihrintzis, V. A. & Hamid, R. Modeling and Management of Urban Stormwater Runoff Quality: A Review. Water Resour. Manag. 11, 136–164, https://doi.org/10.1023/A:1007903817943 (1997).
[65] Calvin, K. et al. IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (Eds.)]. IPCC, Geneva, Switzerland. https://doi.org/10.59327/IPCC/AR6-9789291691647.

Modern coastal stormwater systems often combine gray infrastructure (e.g., pump stations, conveyance tunnels, detention basins, tide gates) with green infrastructure (e.g., bioswales, constructed wetlands, green roofs, infiltration basins). The systems are designed to retain, infiltrate, store, and/or slowly release stormwater while maintaining drainage under tidal influence (Figure 6). In coastal zones, stormwater management must explicitly address the interaction between inland hydrology and coastal water levels to protect built and natural landscapes.[66]

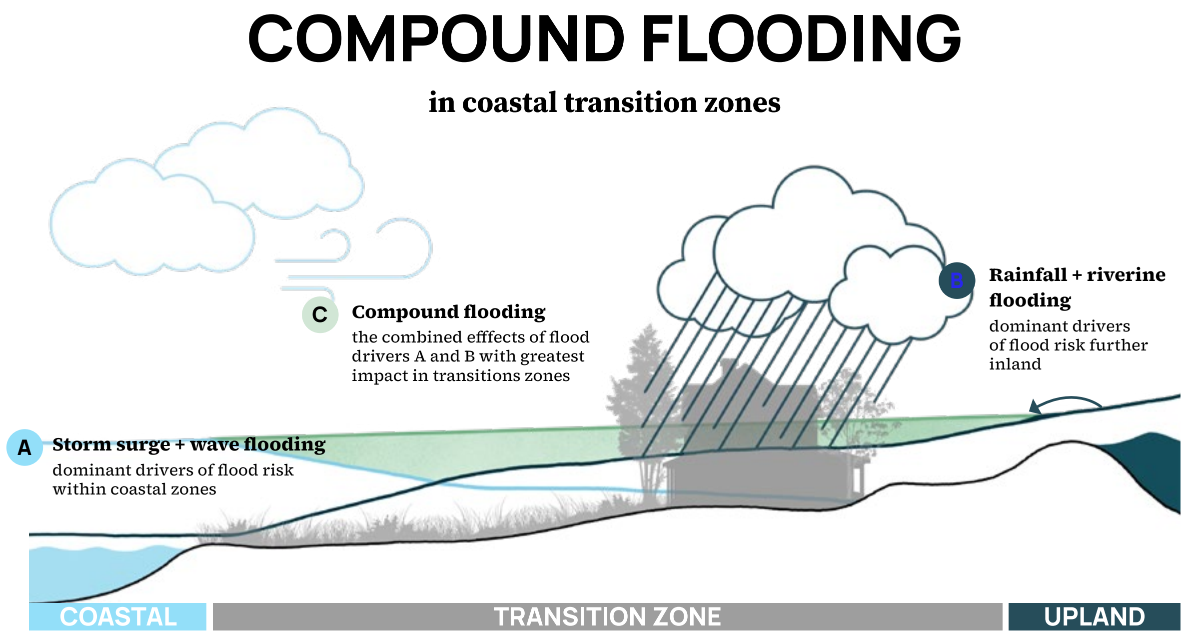


Figure 6: Graphic representation of compound flooding processes, which are becoming increasingly common along coastlines. Heavy inland rainfall combined with coastal storm surges and/or high tides can interact to produce more severe and extensive flooding. Figure adapted from The Water Institute.

Stormwater management infrastructure is typically delivered through incremental upgrades, retrofits, or phased capital projects rather than standalone installations, with construction timelines ranging from months for localized green infrastructure to multiple years for large pump stations, tunnels, or detention basins.[67,68] Monitoring is a standard component of these systems, often measuring flow, water levels, residence time, and water quality parameters such as pH, nutrients, and suspended solids, and in many coastal communities, infrastructure is already instrumented to support flood forecasting, regulatory compliance, and day-to-day operations.[69]

[66] Sebastian, A. Compound flooding. in Coastal Flood Risk Reduction 77–88 (Elsevier, 2022). https://doi.org/10.1016/B978-0-323-85251-7.00007-X.
[67] Design and Construction of Urban Stormwater Management Systems. Manual of Practice No. 77. (2019). American Society of Civil Engineers (ASCE).
[68] Integrated Municipal Stormwater and Wastewater Planning Approach Framework. (2012). U.S. Environmental Protection Agency. https://www.epa.gov/sites/default/files/2015-10/documents/integrated_planning_framework.pdf.
[69] No Adverse Impact: Incorporating Flood Risk Reduction into Stormwater Management. (2018). Association of State Floodplain Managers (ASFPM) & National Oceanic and Atmospheric Administration (NOAA). https://asfpm-library.s3-us-west-2.amazonaws.com/ASFPM_Pubs/ASFPM_NAI_White_Paper_2008.pdf.

Bioswale / vegetated swale: Shallow, vegetated channels that slow, infiltrate, and filter stormwater (a green-infrastructure practice).

Gray infrastructure: Conventional engineered systems (pipes, pumps, tunnels, basins, bulkheads) for flood/stormwater management.

Green infrastructure (GI): As used in the roadmap, refers to nature-based stormwater practices (bioretention, permeable pavement, swales, wetlands) that mimic natural hydrology.

Pump station (stormwater/CSO): Facility that moves large volumes of water; potential node for alkalinity dosing and monitoring.

Abiotic mCDR integration

Stormwater management systems present a distinct and promising opportunity for abiotic mCDR integration particularly because they operate as engineered, partially contained systems with defined flow paths and monitoring locations. Unlike open coastal environments, stormwater networks allow for tighter control over addition of alkalinity and measurement, which is highly valuable for early-stage mCDR projects. A defining characteristic of stormwater systems is their episodic operation with large volumes of water moving through infrastructure during storm events rather than continuously. As a result, scaled abiotic mCDR integration would likely need to rely on weather foresting (e.g., NOAA's Storm Prediction Center) and hydrologic modeling to identify high-rainfall events, prioritize treatment locations, and optimize alkalinity addition.

Outfall (coastal/ wastewater): Discharge point to receiving waters (river, bay, ocean); often a candidate location for sampling or dosing systems.

Both mineral and aqueous alkalinity could be integrated into stormwater systems. The type of alkalinity added may be determined by residence times and chemical factors (e.g., pH) at the project site. Alkalinity dosing could occur directly within stormwater conveyance or storage components, with monitoring placed either within the stormwater system itself or at downstream outfalls where treated water enters receiving coastal waters.

Conceptually, this approach mirrors emerging wastewater-based abiotic mCDR integrations, where engineered water treatment systems are used to control abiotic CDR.[70] Stormwater systems introduce additional complexity due to even-driven operations, but also offer more diverse infrastructure and potentially wider coastal coverage. For example, while conveyance tunnels, detention basins, drainage ponds, and ecotone levees may provide larger scale project sites, smaller-scale research projects could extend to distributed infrastructure such as green roofs or localized drainage features. Stormwater integrations are likely to follow MRV for wastewater to examine how much CDR occurs in the contained system by neutralizing CO_2 from plant biomass and organic matter in the stormwater. If neutralization is occurring in the system, initial research projects would need to understand more about the source of acidity to ensure the process is in fact CDR. This abiotic mCDR integration's unique benefit to stormwater management lies in its potential to neutralize stormwater and allow coastal outfalls to better comply with discharge permits and ocean health initiatives.

Stormwater infrastructure is managed at different geographic levels, so there is no centralized assessment of U.S. stormwater retention capacity, particularly stormwater management systems that integrate gray and green infrastructure. However, the scale of existing and planned stormwater investments (see case studies) suggest that this sector represents substantial, underexplored opportunities. Given this uncertainty, small-scale pilot projects are encouraged to inform feasibility, monitoring strategies, and operations development while other entities take on scaling assessments.

[70] Cai, W.-J. & Jiao, N. Wastewater alkalinity addition as a novel approach for ocean negative carbon emissions. The Innovation 3, https://doi.org/10.1016/j.xinn.2022.100272 (2022).

Geographic scope

Many coastal states in the United States have strong prospects for integrated CDR projects. Here, we discuss four example states illustrative of different coastal resilience projects and policy environments. We selected case studies based on 1) policy, 2) economic and geographic, and 3) need and capacity criteria (Figure 7). The policy-related parameters highlight the motivation for a state to pursue resilience and mitigation projects, and the mechanisms (e.g., regulatory processes) states must use to pursue integrations. The economic and geographic criteria capture the role the coastline plays in a state's economy, and therefore how valuable the coastline is to protect. Need and capacity factors were meant to capture the risk vulnerability to coastal issues for each state as well as the expertise to pursue innovative solutions. Details on each criterion, the data and scores for each state, and any data processing, can be found in Appendix A.

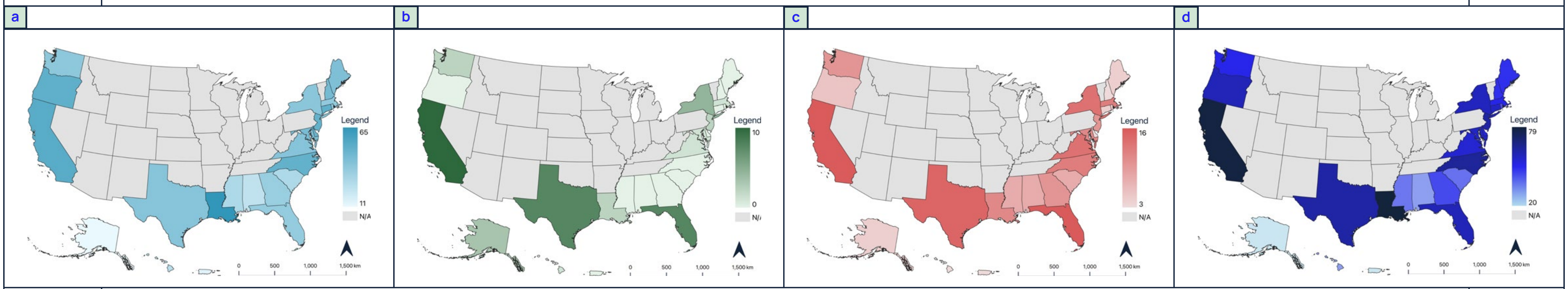
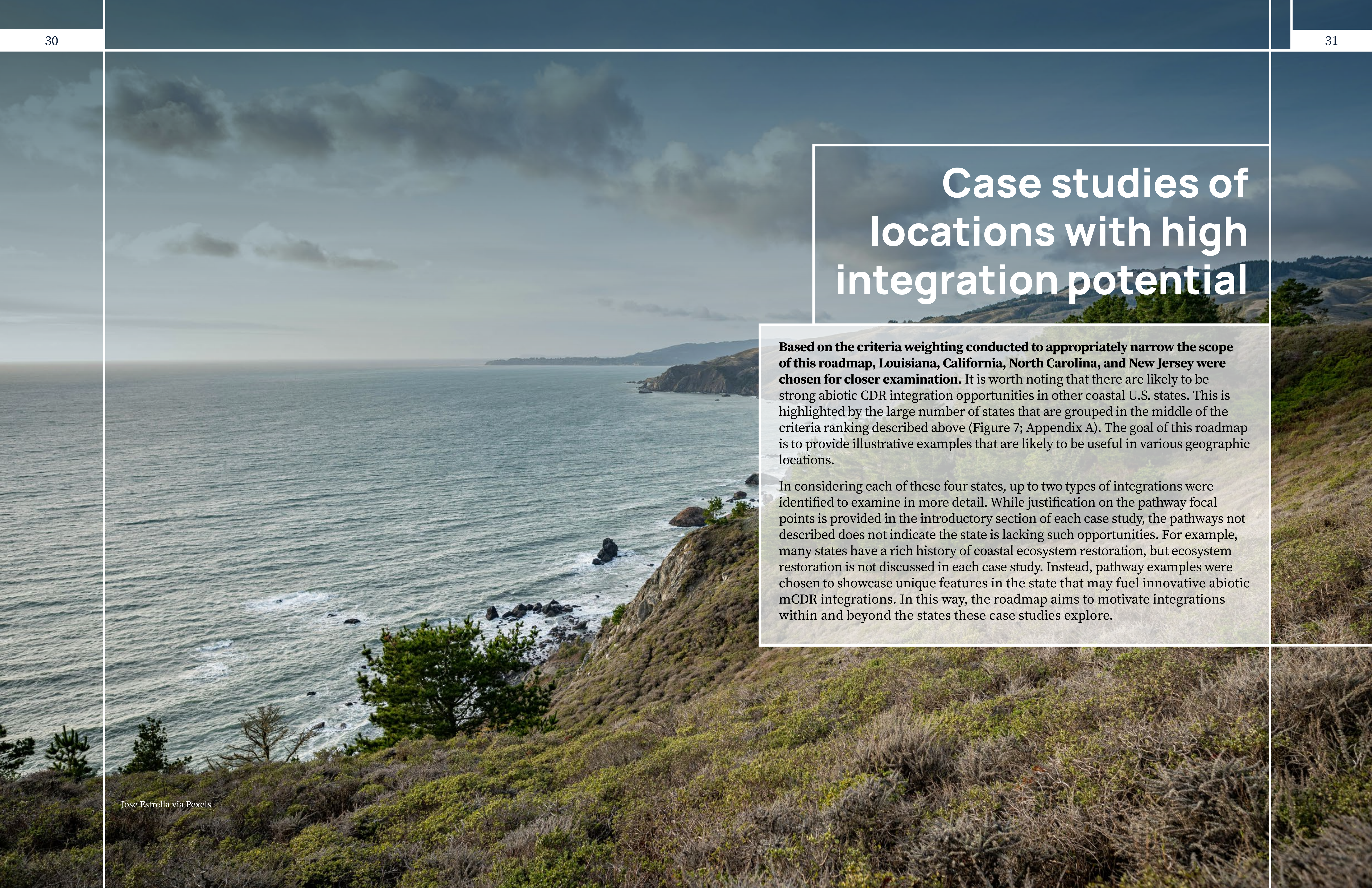


Figure 7: Geographic distribution of the weighted scores, where a) is the policy-focused criteria only, b) is the economic and geographic criteria only, c) is the need and capacity criteria only, and d) are the compiled weighted scores. The weighted scores were used as a means to focus the scope of this roadmap on illustrative examples for abiotic mCDR coastal resilience integrations. Many coastal states have robust coastal resilience portfolios and enabling conditions (see Appendix A) that could be amenable to abiotic integrations. As described in introductory materials, weighted scores do not consider opportunities for biotic or land-based CDR approaches, which could also be significant in these coastal states.



Jose Estrella via Pexels

Case studies of locations with high integration potential

Based on the criteria weighting conducted to appropriately narrow the scope of this roadmap, Louisiana, California, North Carolina, and New Jersey were chosen for closer examination. It is worth noting that there are likely to be strong abiotic CDR integration opportunities in other coastal U.S. states. This is highlighted by the large number of states that are grouped in the middle of the criteria ranking described above (Figure 7; Appendix A). The goal of this roadmap is to provide illustrative examples that are likely to be useful in various geographic locations.

In considering each of these four states, up to two types of integrations were identified to examine in more detail. While justification on the pathway focal points is provided in the introductory section of each case study, the pathways not described does not indicate the state is lacking such opportunities. For example, many states have a rich history of coastal ecosystem restoration, but ecosystem restoration is not discussed in each case study. Instead, pathway examples were chosen to showcase unique features in the state that may fuel innovative abiotic mCDR integrations. In this way, the roadmap aims to motivate integrations within and beyond the states these case studies explore.

CASE STUDIES:

Louisiana

Weighted Score: 78

Louisiana - Beau Runnels via Pexels

Ports: Harbor facilities critical to state economies; part of economic weighting for enabling conditions. Can also be referred to as working waterfronts.

Existing resilience projects

Louisiana's coastline totals 7,721 miles and supports over two million coastal residents.[1] The United States Geological Survey equates land loss in Louisiana in recent years to a football field-worth of wetlands disappearing into water every 100 minutes.[71] This dire rate of erosion, subsidence, and sea level rise, causes devastating storm surges and flooding across the coastline. Given the rate of land loss, the state is a particularly valuable case study for embedded CDR with ecosystem restoration.

Ecosystem restoration

There is a suite of approaches to restore ecosystems in Louisiana, particularly marshlands. Ecosystem restoration includes marsh creation, ridge and landbridge restoration, river diversion, and hydrologic restoration.[48] From 2017 to 2023, there have been 140 coastal resilience projects completed, including nearly 200 million cubic yards of sediment placed.[48] The resources included in the Coastal Protection and Restoration Authority's (CPRA) Draft 2027 Annual Plan outline that since 1999, 38 marsh creation projects have been completed and 15 are listed as pending. These marsh creation projects include placing dredged sediment and plantings in degraded marsh areas that are now open water.[48] Analysis of marsh creation projects indicate that the created marshlands are often effective at mirroring natural biodiversity[72,73] and may even be more effective for improving water quality.[74] Post-creation monitoring has indicated that these projects are generally successful at combating erosion; for a West Lake Boudreaux project (completed in 2009, 20 year expected lifetime), pre-

[71] Couvillion, B. R., Beck, H., Schoolmaster, D. & Fischer, M. Land Area Change in Coastal Louisiana (1932 to 2016). Scientific Investigations Map (2017). https://doi.org/10.3133/sim3381.
[72] Edwards, K. R. & Proffitt, C. E. Comparison of wetland structural characteristics between created and natural salt marshes in southwest Louisiana, USA. Wetlands 23, 344–356, https://doi.org/10.1672/10-20 (2003).
[73] Keppeler, F. W. et al. Can biodiversity of preexisting and created salt marshes match across scales? An assessment from microbes to predators. Ecosphere 14, e4461, https://doi.org/10.1002/ecs2.4461 (2023).
[74] Cheng, J. Z. & White, J. R. Dredge-material created coastal marshes are more effective at improving water quality than natural marshes in early-stage development. Ecol. Eng. 185, 106814, https://doi.org/10.1016/j.ecoleng.2022.106814 (2022).

construction erosion from 1998 to 2004 was occurring at a rate of -64.85 ft/yr, and post-construction monitoring showed slight land mass gain from 2008 to 2012 of 0.03 ft/yr.[48] The 2023 Coastal Master Plan outlines a suite of proposed projects that could advance toward implementation as funding becomes available, recognizing that some projects will require additional feasibility analyses prior to engineering and design, while others may proceed more directly to engineering and construction. The Plan includes substantial community engagement, which should be continued if projects advance to the implementation stage (see Towards implementation section). Of these projects, the Plan notes that 23 of the 41 proposed restoration projects are focused on marsh creation (Figure 8), for a total of $16 billion in expected need over the next 50 years. Cost, sediment availability, and political decisions can all impact a marsh creation project.

Louisiana 2023 coastal master plan projects

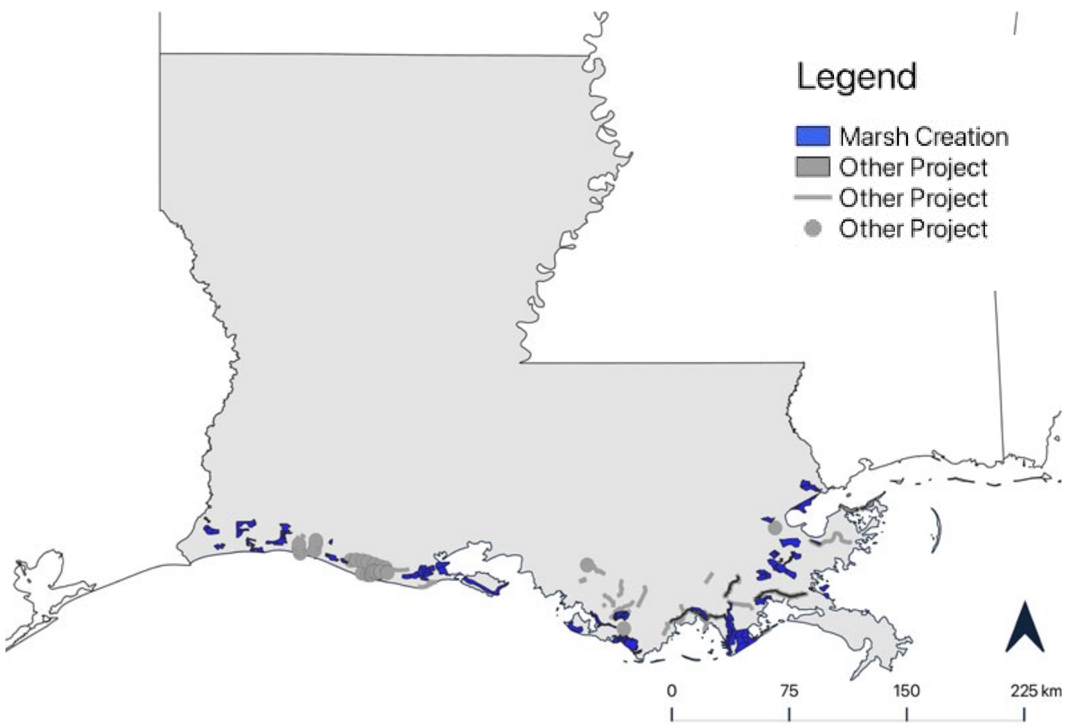


Figure 8: Geospatial distribution of 23 proposed coastal marsh creation projects, selected from a portfolio of 77 restoration and risk reduction projects associated with the state's 2023 Coastal Master Plan

CASE STUDIES:

Louisiana

Embedding CDR into ecosystem restoration in Louisiana would leverage large sediment placements. **Alkaline sediment could be used to supplement sediment placements, which may help with reducing sediment demand, and provide carbon benefits to carbon-intensive adaptation projects.** In Louisiana, limestone is the most readily available alkaline substrate that could be used in such an integration, given that nearby Texas and Florida are the leading producers of crushed limestone rock in the United States.[75]

Research priorities for early integrations

1. **Evaluate Louisiana-relevant alkaline sediment sources for marsh creation.** Assess availability, cost, transport energy, and mineral composition of substrates compatible with CPRA marsh creation (e.g., dredged sediments supplemented with limestone from Gulf Coast), including trace metal content relevant to wetland placement.
2. **Quantify mineral dissolution and alkalinity generation in deltaic marsh conditions.** Measure dissolution rates and carbon update potential of alkaline additions under Louisiana-specific conditions, including organic-rich sediments, brackish to saline gradients, and intermittent flooding typical of created marsh platforms.
3. **Assess effects of alkalinity additions on marsh elevation, compaction and longevity.** Examine how mineral additions influence sediment consolation, subsidence rates, and resistance to erosion and storm-driven redistribution, relative to the design lifetimes of Louisiana march creation projects.
4. **Integrate carbon monitoring into existing marsh performance and compliance monitoring.** Develop MRV approaches that leverage CPRA post-construction monitoring (elevation change, vegetation establishment, water quality) to quantify carbon outcomes without creating parallel or duplicative monitoring programs.
5. **Identify near-term pilot opportunities within planning Louisiana marsh creation projects.** Screen proposed and pending CPRA marsh creation sites for early integration based on sediment values, construction timelines, permitting readiness, and proximity to material sources, enabling low-risk demonstrations within existing resilience workflows.

Enabling policies

Louisiana's coastal resilience policies, both state and federal, provide the vision, coordination, and funding that will continue to support ecosystem restoration projects with opportunities for embedded CDR. In 1990, the U.S. Congress passed the Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA), which established federal and state coordination (see Permitting landscape section) and dedicated funding through the Sport Fish Restoration and Boating Trust Fund to the United States Army Corps of Engineers (USACE) with a state match (typically 15%) to support the implementation of restoration projects. Following Hurricanes Katrina and Rita in 2005, Louisiana passed Act 8, which created the CPRA and mandated the agency to create a coastal master plan every five years (later law changed this cadence to every six years). The first Coastal Master Plan was approved in 2007, and the most recent plan was published in 2023. Louisiana is the only state to have a mandated plan, which provides a strategic vision for coastal resilience, outlining priority projects for the coming years.

Permitting landscape: The collective agencies, laws, and processes (federal, state, local) governing approvals for coastal and stormwater projects.

Two additional pieces of federal legislation were passed that provide funding to Louisiana, as well as other Gulf states, related to oil and gas recovery. In 2006, the Gulf of Mexico Energy Security Act (GOMESA) was created to share federal offshore oil and gas revenue with four Gulf states to be used for conservation and restoration. Louisiana dedicates all its funding to the Coastal Master Plan projects. In 2012, the Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States (RESTORE) Act was passed in response to the Deepwater Horizon oil spill. The RESTORE Act provides 80% of revenue generated through Clean Water Act penalties to the Gulf Coast Restoration Trust Fund to be divided among various activities to support coastal resilience in the Gulf. This funding will expire in 2031 when the Clean Water Act penalties installments are completed. From these two funds, Louisiana receives some $90 million per year on average. While federal revenues from GOMESA and the RESTORE Act

RESTORE Act: Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States Act

[75] Willet, J. Stone, Crushed. (2018). United States Geological Survey. https://pubs.usgs.gov/myb/vol1/2018/myb1-2018-stone-crushed.pdf

Lafayette, LA - Tom Fournier via Pexels

Sediment diversion (Louisiana): Engineered openings in levees to deliver sediment- and/or nutrient-rich river freshwater to sinking estuarine wetlands for land building.

Clean Water Act (CWA) Sections 401/404: U.S. water quality certifications (401) and permits for discharge of dredged/fill material (404) administered by USACE/states.

National Environmental Policy Act (NEPA): U.S. law requiring environmental review (environmental assessment / environmental impact statement) for major federal actions; often applies to restoration and large pilots.

Executive order (EO): Governor-issued directive that can set climate/resilience policy where legislation hasn't been passed.

provide a critical and ongoing funding base for Louisiana's coastal program, large-scale project implementation is often financed through state general obligation bonds, as reflected in the state's 2027 Capital Outlay priorities to achieve consistent budgets of over $1 billion.

In addition to statutory authorities and funding mechanisms, Louisiana has also invested in technical and programmatic analyses that help enable the integration of emerging carbon mitigation projects into coastal restoration. For example, CPRA has supported recent evaluations of the technical applicability and financial feasibility of carbon accreditation for coastal restoration projects, assessing how existing and evolving voluntary carbon market frameworks may align with the state's restoration portfolio.[76] While these efforts do not constitute binding policy, they provide an important analytical foundation that informs future decision-making, identifies opportunities and constraints, and positions Louisiana to adapt its coastal program as markets, methodologies, and regulatory frameworks evolve.

While Louisiana has strong potential for integrations due to vision, coordination, and funding, administration shifts can jeopardize projects in the state. For example, in 2020, the former governor signed a net-zero executive order (EO JBE 2020-18) which created the Climate Initiatives Task Force, and oversaw the final permitting process for the largest state ecosystem restoration project, the Mid-Barataria Sediment Diversion Project. Both actions are favorable for coastal resilience and CDR integration. However, the current state administration has since halted the project, signaling a potential shift in priorities for coastal resilience projects despite previous bipartisan support.

Permitting landscape

Ecosystem restoration (and related CDR integrations) on the Louisiana coast requires coordinated review among federal (see Box 1), state, and local agencies because most projects occur in wetlands or navigable waters. The USACE is the primary federal authority, issuing Clean Water Act Section 404 permits for dredged or fill material and Rivers and Harbors Act Section 10 permits for work in navigable waters. Larger or more complex projects undergo environmental review under the National Environmental Policy Act (NEPA), typically through an environmental assessment or environmental impact statement. USACE would coordinate any other necessary consultations for Essential Fish Habitat or the Endangered Species Act.

[76] Viability of Carbon Accreditation for Coastal Restoration in Louisiana. (2025). The Water Institute.

BOX 1

How Federal Authority Intersects with State Regulatory Processes

For coastal resilience projects that occur on the coastline, USACE will be the main federal permitting agency who will run consultations with other federal agencies such as the U.S. Fish and Wildlife Service and NOAA National Marine Fisheries Services on Essential Fish Habitat and the Endangered Species Act. If the activities take place in a National Marine Sanctuaries (NMS) projects must also engage with staff at those agencies. It is best practice to consult NOAA NMS staff even if the activity could affect an existing NMS given some sanctuaries have more stringent protections. For outflow-based projects (e.g., stormwater management), the U.S. Environmental Protection Agency (EPA) oversees the National Pollutant Discharge Elimination System (NPDES), which was established by the Clean Water Act. The majority of states implement this regulatory process, which is further discussed in the case studies. If federal funding is received or the project moves through a federal permitting process, NEPA will likely also be considered to limit overall environmental impact. Project developers should review online resources, such as those generated through interagency processes or by NMS, during early project development for more guidance.

National Pollutant Discharge Elimination System (NPDES): Permit program for discharges to waters (MS4s, waste water treatment plants, industrial), implemented by SWRCB/regional boards in California and by NJDEP in New Jersey.

State permitting is centered on the Coastal Use Permit (CUP), administered by the Office of Coastal Management for any project within the Louisiana Coastal Zone. The CUP process is closely linked with federal permitting through the Joint Permit Application, which allows applicants to submit engineering plans, environmental analyses, sediment evaluations, and site information in a single consolidated package. All restoration actions must also demonstrate consistency with the state's Coastal Master Plan.

A foundational driver of this coordination is the CWPPRA; since the early 1990s, CWPPRA has funded, designed, and constructed hundreds of wetland restoration projects across coastal Louisiana. Because these projects required repeated, large-scale permitting actions, CWPPRA helped institutionalize a formal, interagency review structure that is now used for nearly all restoration projects in the state. This structure includes regular coordination among USACE, NOAA National Marine Fisheries Service, the US Fish and Wildlife Service, the EPA, CPRA, and state coastal management agencies. As CWPPRA projects advanced, agencies standardized permit-review expectations, sediment testing protocols, environmental documentation formats, and consultation procedures, creating a predictable permitting pathway that current restoration initiatives continue to rely upon.

CASE STUDIES:

California

Weighted Score: 78

Montara, California - Umay Isik via Pexels

Existing resilience projects

California has nearly 3,500 miles of coastline, which serves as an economic and cultural hub for the state.[1] Most of California's coastline is along the open ocean, with the exception of 400 miles of protected coastline in the San Francisco Bay.[47] The southern half of the state hosts more developed coastlines. This diversity of coastline infrastructure presents embedded CDR opportunities for all of the coastal resilience pathways; however, to narrow the scope of this roadmap, this section focuses on opportunities that can be pursued throughout the coastline rather than just in protected areas. Therefore, the integration opportunities presented here span living shorelines and stormwater management.

Living shorelines

While living shorelines are often implemented in protected environments, California's coastal dune systems function as living shorelines along much of the open coastline.[34,77] Approximately one fourth of California's coastline is backed by dunes,[78] though many of these systems have been degraded or eliminated for coastal development. The California Coastal Dune Science Network currently tracks 13 implemented dune coastal resilience projects, 11 in planning, and 3 in progress distributed along the state's coastline (Figure 9).

[77] Winters, M. A., Leslie, B., Sloane, E. B. & Gallien, T. W. Observations and Preliminary Vulnerability Assessment of a Hybrid Dune-Based Living Shoreline. J. Mar. Sci. Eng. 8, 920, https://doi.org/10.3390/jmse8110920 (2020).

California coastal dune science network projects

Figure 9: Graphical representation of 25 dune restoration projects across California recorded by the California Coastal Dune Science Network.

Coastal dune systems represent a dynamic interface shaped by wind, waves, and vegetation, with distinct zones that influence both sediment stability and biogeochemical processes. Pioneer dunes closest to the shoreline are frequently disturbed by tides and storms, and therefore support sparse, salt-tolerant vegetation.[79] Further inland, increasing plant cover forms dune mats and foredunes often dominated by grasses and perennial species that enhance sediment retention and stability.[80] In mature systems with ample space, shrub and forest communities develop on backdunes, creating higher-elevation, more stable landforms.[80] Where geomorphic and wind conditions are favorable, such as wide beaches and winds that allow for sand to move, dune restoration may involve relatively low-intervention approaches, including limiting breach grooming and other activities that disrupt sediment movement, as demonstrated by the Santa Monica Beach restoration pilot project.[81] In more sediment-limited or erosion-prone settings, such as the Cardiff Living Shorelines Project, dune restoration often relies on hybrid approaches that combine engineered berms with placed sediment to establish the initial dune form.[77] These approaches are increasingly relevant in California, where long-term alteration of sediment supply has led to widespread beach narrowing,[82] increasing reliance on costly sediment-intensive beach nourishment practices.[81,83]

Sediment supply: Conditions of low/high availability of transportable sand/mud needed to maintain dunes and marshes.

Abiotic mCDR integration in dune systems would focus on vegetated dune zones

[78] Cooper, W. S. Coastal Dunes of California. in Coastal Dunes of California (ed. Cooper, W. S.) vol. 104 0 (Geological Society of America, 1967).
[79] Sawyer, J. O. & Keeler-Wolf, T. A manual of California vegetation. https://digitalcommons.usu.edu/aspen_bib/1852 (2008).
[80] Pickart, A. & Barbour, M. Beach and Dune. in Terrestrial Vegetation of California 155–179, https://doi.org/10.1525/california/9780520249554.003.0006 (2007).
[81] Johnston, K. K., Dugan, J. E., Hubbard, D. M., Emery, K. A. & Grubbs, M. W. Using dune restoration on an urban beach as a coastal resilience approach. Front. Mar. Sci. 10, https://doi.org/10.3389/fmars.2023.1187488 (2023).
[82] Patsch, K. & Griggs, G. Littoral Cells, Sand Budgets, and Beaches: Understanding California's Shoreline California Department of Boating and Waterways California Coastal Sediment Management Workgroup (2006). https://www.coastal.ca.gov/coastalvoices/resources/2006-LittoralCells.pdf
[83] Ludka, B. C., Guza, R. T. & O'Reilly, W. C. Nourishment evolution and impacts at four southern California beaches: A sand volume analysis. Coast. Eng. 136, 96–105 (2018).

where biological activity and soil moisture can facilitate dissolution of mineral alkalinity additions. Research on the California dune system is relatively young and therefore little is known about spatial variability in soil pH and carbonate chemistry across dune systems. Studies from other regions indicate that soil pH tends to decline as dune systems mature.[84] In these settings, mineral addition could neutralize CO_2 produced through plant and microbial respiration, generating alkalinity in porewaters that may subsequently mix with coastal waters. Placement of alkaline sediment within stabilized dune features may also support resilience objectives by enhancing sediment retention and long-term dune accretion. The effectiveness and ecological compatibility of any addition in dune systems is strongly influenced by grain size relative to native sediments, as deviations from natural grain size distributions can alter wind-driven transport and dune morphology.[86]

Dune projects in California may emphasize dune restoration rather than dune creation, often through the removal of invasive vegetation and reestablishment of native plant communities. While this roadmap does not explore dune restoration methods in detail, the same integration logic applies, though the timing and magnitude of alkalinity generation may depend on how quickly vegetation and soil conditions suitable for dissolution are reestablished. In some systems, mineral addition may also remediate soil acidification associated with invasive species, or prior restoration activities based on herbicides, as suggested by recent California studies.[87]

While this section focuses on dune-based integrations, other living shoreline projects that require sediment, fill, or stabilization may also be suitable candidates for embedded mCDR. In California, these opportunities are most likely to occur in lower-energy environments (see examples in New Jersey and North Carolina) like inlets and systems such as the San Francisco Bay, where living shoreline projects already incorporate sediment placement. Integrating abiotic mCDR into these projects could diversify supply chains to sediment-starved beaches[88] while generating additional carbon benefits without fundamentally altering project design.

[84] Isermann, M. Soil pH and species diversity in coastal dunes. Plant Ecol. 178, 111–120, https://doi.org/10.1007/s11258-004-2558-8 (2005).
[85] Griggs, G. & Kinsman, N. Beach widths, cliff slopes, and artificial nourishment along the California Coast. 84, (2016).
[86] Hesp, P. Foredunes and blowouts: initiation, geomorphology and dynamics. Geomorphology 48, 245–268, https://doi.org/10.1016/S0169-555X(02)00184-8 (2002).
[87] Parsons, L. & Becker, B. Invasion by Ammophila arenaria alters soil chemistry, leaving lasting legacy effects on restored coastal dunes in California. Invasive Plant Sci. Manag. 14, 1–44, https://doi.org/10.1017/inp.2021.16 (2021).
[88] California Coastal Sediment Master Plan (2021). https://dbw.parks.ca.gov/pages/28702/files/CSMW%20Master%20Plan%20Report%2020210120.pdf.

Research priorities for early integrations:

1. **Establish baseline physical and geochemical conditions across California dune systems.** Compile spatial data on grain size distribution, soil pH, carbon content, and existing vegetation across restored and unrestored dunes using existing data where possible. Utilize these data to develop approaches to measure alkalinity and porewater export.

2. **Assess alkaline feedstock compatibility with dune sand characteristics.** Evaluate potential mineral additions relative to natural dune grain sizes, including energy requirements for grinding, transport feasibility, and suitability for placement within these wind-influence systems.

3. **Model sediment placement and transport under coastal dynamics.** Simulate how alkaline sediment additions behave under wind-driven migration, storm overwash, and tidal influence, with attention to placement location relative to pH gradients and vegetation zones.

4. **Evaluate impacts of mineral addition on dune vegetation establishment and health.** Test responses of native dune plants across successional stages to altered soil chemistry, including thresholds that support dissolution while maintaining plant stability and invasive species resistance.

5. **For other living shoreline projects, quantify sediment dynamics and existing project-specific monitoring.** Assess how much sediment is used for grading, fill, and stabilization in California living shorelines projects in bays and inlets (e.g., San Francisco Bay). Evaluate the feasibility and carbon benefits of substituting or supplementing these materials with mineral-based alkalinity within existing design and permitting frameworks.

CASE STUDIES:

California

Stormwater management

In California, both green and gray solutions may hold opportunities for stormwater management. For gray infrastructure, the City of San Francisco is an interesting use case — it is the only major city in California that has combined sewer and stormwater systems, as it developed prior to sewer systems. Combined sewer and stormwater systems can be beneficial to ocean health when functioning properly, as stormwater is treated prior to disposal in the waterway. However, during large rain events, these combined systems can lead to combined sewer overflows (CSOs), where water is discharged with minimal treatment. With increasing storm inundation, there are a number of active projects to better manage CSOs in the San Francisco Bay Area. The San Francisco Public Utilities Commission has undertaken the Sewer System Improvement Project, a 20-year and multi-billion-dollar program to upgrade its sewers and better manage CSOs, including upgrading its wet-weather treatment plant and enhancing pump stations, some of which are underway.

Cities in California have large stormwater retention tanks that store stormwater to allow for release once flooding or high-water levels subside. These structures have enormous capacity. **For example, structures in the City of Los Angeles can hold 27 billion gallons of water under normal conditions with projections that the city could double that capacity by 2035.**[89]

Green infrastructure for stormwater management may also hold opportunities for CDR integration. For example, some locations, such as Calera Creek in Pacifica, are also utilizing wetlands as stormwater management opportunities. Other green retention infrastructure systems that could serve as small-scale pilots for integrations include rain barrels and cisterns, green roofs, permeable pavement, and biotreatment through rain gardens, bioretention units, bioswales, etc. These green infrastructure holding ponds may present similar opportunities for CDR integrations and perhaps even more favorable pH conditions to support mineral-based alkalinity.

[89] Consultants, G. & Corp, C. Stormwater Capture Master Plan. (2015). https://www.ladwp.com/sites/default/files/2023-08/LADWPStormwaterCaptureMasterPlan_MainReport_101615.pdf.

Research priorities for integrations:

1. **Inventory and characterize candidate stormwater infrastructure.** In coordination with California municipalities, map combined sewer systems, stormwater retention tanks, and green infrastructure (e.g., wetlands, bioretention basins, cisterns) to identify locations with sufficient residence time, access points, and operational flexibility for pilot integrations.

2. **Model storm-driven flow regimes and residence times under California climate conditions.** Quantify flow variability during dry weather, moderate storms, and extreme precipitation events to inform dosing strategies and identify infrastructure segments where alkalinity addition would be most effective and controllable.

3. **Evaluate material delivery strategies and implications for MRV.** Compare mineral-based and aqueous alkalinity additions across gray and green stormwater systems, assessing dissolution efficiency, operational constraints, and how material form influences MRV feasibility under variable flow conditions.

4. **Establish baseline stormwater geochemistry, acidity drivers, and potential additional co-benefits.** Characterize pH, alkalinity, and other water quality parameters across stormwater sources, with particular attention to identifying sources of acidity (e.g., atmospheric deposition, urban runoff, organic matter) that influence alkalinity demand and CDR potential. This should also include compiling or collecting data from coastal outflows during storm events to understand the co-benefit opportunities to reduce coastal stressors from outflows associated with the carbonate chemistry (e.g., coastal ocean acidification).

5. **Assess regulatory, operational, and public health constraints for municipal deployment.** Evaluate how proposed integrations interact with NPDES permitting, CSO compliance requirements, and water quality standards in California, including thresholds for trace metals and downstream receiving waters, to ensure compatibility with existing stormwater management objectives.

Baseline (for MRV): Pre-project measurement of carbon, ecosystem, and social conditions used to compare against pilot results to quantify net change.

CASE STUDIES:

California

Enabling policies

California has robust legislation to support coastal resilience, climate action, and, more recently, carbon markets, all of which support the successful integration of CDR into coastal resilience projects. The state, under Senate Bill (SB) 1, has provided funding for local governments in California's coastal zones and along the San Francisco Bay shoreline to develop plans for sea level rise, some of which are already underway. The subsequent SB 272 requires state agency approval of these plans, which must be submitted for approval by January 1, 2034. Adaptation projects and strategies within approved Plans will be further prioritized for state funding.

In addition, the California Natural Resources Agency (CNRA) recently updated its California Climate Adaptation Strategy. The CNRA works in partnership with the California Air Resources Board, which in part puts forth and manages updates to the state's Natural Working Lands Inventory and the Cap-and-Invest multi-emission trading systems to thereby inform how restoration and industry in California connect to the overall carbon accounting for the state.

There are a few novel policies in California that unlock funding, which could be utilized for these integrations. In 2022, SB 852, the Climate Resilience Districts Act, allows local governments the ability to create new financing tools and structures to support climate resilience projects such as fees, charge, or voter-approved supplemental tax revenue. Also in 2022, SB 198 created the Local Transportation Climate Adaptation Program, which provides competitive grants to local agencies for the development and implementation of projects adapting local transportation infrastructure, including but not limited to ports. In fiscal year 2026–27, the California Department of Transportation plans to allocate $34.5 million for climate adaptation and planning through their Sustainable Transportation Planning Grant program. In 2024, Prop 4 created a $10 billion climate bond, which aims to fund coastal resilience. Other bills have been passed to require accounting and generate revenue from private actors in California through SB 261 and 253, but they are currently on pause and being argued in court.

California's emissions reduction targets are ambitious and serve as motivation to pursue adaptation projects that have mitigation integrations. In 2022, Assembly Bill (AB) 1279 codified the state's climate targets into law. AB 1279 requires California to achieve net-negative emissions after 2045. This net-negative goal sets a hard target of at least 85% emissions reduction below 1990 levels, which also means the remaining 15% must be addressed with CDR. California's statutory requirement for net-negative emissions after net zero creates a direct role for

CDR in law, rather than leaving removal as an implied goal. Alongside AB 1279, California also passed SB 905 in 2022 which charges the California Air Resources Board with building a carbon management framework for the state to be able to assess various carbon projects; the build broadly defines CDR. Numerous other bills have been introduced around CDR and carbon management, two policy topics that are likely to continue growing in the state. Overall, these carbon and coastal resilience policies set the state apart by providing the necessary enabling conditions for leveraging opportunities to integrate CDR.

CASE STUDIES:

California

Permitting landscape

Permits for embedded CDR projects will need to mirror the permitting structure of coastal resilience projects which will likely include federal (see Box 1), state, and local permits. In California, the regulatory framework for coastal restoration and stormwater management generally involves overlapping permitting pathways overseen by a variety of state agencies depending on the project and the resources used to fund the project. Projects such as living shorelines and dune restoration fall under the jurisdiction of the California Coastal Commission and, in San Francisco Bay, the San Francisco Bay Conservation and Development Commission (BCDC). Stormwater retention, infiltration, and discharge infrastructure are primarily regulated under the NPDES by the State Water Resources Control Board and the nine Regional Water Quality Control Boards. Other agencies may intersect with either of these project types including the agencies like the State Lands Commission, California Department of Fish and Wildlife, and the Office of Historic Preservation. The California Environmental Quality Act (CEQA) will also intersect with these projects when a California state agency funds, permits, approves, or carries out a project.

Regional Water Quality Control Boards (California): Nine boards under SWRCB implementing NPDES and water quality standards regionally.

Efforts are being taken to streamline these processes for restoration projects that meet certain requirements, known as efforts to reduce green tape. This includes the CEQA Statutory Exemption for Restoration Projects, which is extended to 2030 through SB 174 when certain requirements are met. California's Department of Fish and Wildlife's Cutting the Green Tape Program is responsible for coordinating with lead agencies for projects seeking concurrence through the Statutory Exemption for Restoration Projects. The complexity presented here is illustrative and not exhaustive. Project developers looking to pursue an integration in the state are encouraged to leverage coastal resilience permitting expertise, reach out to permitting agencies early in the process, and ask representatives what other agencies they should be talking to in order to scope their permitting process.

Living shorelines and dune restoration permitting

Projects that modify coastal dunes, beaches, or wetlands are considered "development" under the California Coastal Act, and the McAteer-Petris Act for the San Francisco Bay, and generally require a coastal development permit (CDP). The CDP process evaluates potential impacts to coastal resources, public access, and shoreline stability; applications are reviewed either by local governments with certified Local Coastal Programs or directly by the California Coastal Commission in areas of retained jurisdiction. Embedded CDR with dune restoration and living shoreline initiatives must demonstrate consistency with the Coastal Act's policies on habitat protection, erosion control, and sea level rise adaptation.

The California Coastal Commission's guidance outlines expectations for coastal resilience projects, emphasizing hazard analysis, adaptation planning, and nature-based design approaches. Applicants are typically required to submit detailed site plans, hydrologic and geomorphic assessments, and habitat restoration specifications. In the San Francisco Bay region, similar shoreline adaptation projects are reviewed under the authority of the BCDC. State law gives BCDC the authority to issue or deny permits for any projects that "place fill...extract materials, or...make any substantial change in use of any water, land or structure" within its jurisdiction.

In addition to the CDP, other regulatory processes may apply to living shoreline projects given the sediment addition to the ecosystems. For example, the Nine Regional Water Boards may intersect with sediment fill and adaptation projects through the Clean Water Act. Helpful resources outlining these interactions in wetlands and other basins can be found on the Water Control Board plans and policy webpage. More information on the San Francisco Bay, particularly around intersecting authorities at the state and federal levels for these projects, can be found here.

Stormwater retention and discharge permitting

Infrastructure for stormwater capture, retention, infiltration, or discharge is regulated through the NPDES program, established under the federal Clean Water Act and implemented in California by the SWRCB Discharges from municipal separate storm sewer systems, industrial sites, and construction activities are authorized under statewide or regional permits administered by the relevant Regional Water Quality Control Boards. For San Francisco, the combined system, including both sanitary and stormwater flows, is regulated under a single NPDES wastewater discharge permit issued to the San Francisco Public Utilities Commission by the San Francisco Bay Regional Water Quality Control Board. There are notable exclusions to the described oversight where outfalls flow into federal waters, such as in San Francisco or Los Angeles, where joint state-federal permits are issued. EPA will also permit on tribal lands.

Stormwater discharges and associated permitting information are detailed by the State Water Resources Control Board under its Storm Water Program and NPDES guidance portals. Joint federal-state permit and more general NPDES information is available on the EPA's website.

CASE STUDIES:

North Carolina

Weighted Score: 64

Surf City, NC - Curtis Adams via Pexels

Existing resilience projects

Out of the four case studies presented in this roadmap, North Carolina has the lowest number of residents spanning its 3,375 miles of coastline, yet the greatest number of coastal events since 2018, with damages totaling over $1 billion.[1] This prevalence of disasters along with its policy frameworks has pushed the state into a leadership role for certain coastal resilience pathways.

Living shorelines

North Carolina's coastline, with its large, shallow, estuarine environments, creates the ideal low-energy system for living shorelines. The North Carolina Coastal Federation notes that in 2024, **the state implemented 55,000 linear feet (about 10 miles) of living shorelines across 242 projects.** A closer look at a number of the largest living shoreline projects, Whittaker Pointe, Marine Corps Air Station Cherry Point, and Fort Macon State Park, shows that all of these projects included the addition of sand substrate. Quantitative sand supply to these systems was not reported, but was likely significant given its use for TLP on extensive marsh habitat or for regrading behind a sill. In North Carolina, living shorelines are installed on private property and for a range of public-sector clients, including the United States Marine Corps and state agencies.

Research priorities for early integrations:

1. **Quantify sand volumes and material sources used in North Carolina living shoreline projects.** Compile data, including through permits, interviews, and engineering plans for recent large-scale projects (Whittaker Pointe, MCAS Cherry Point, Fort Macon State Park) to characterize sand placement volumes, sourcing practices, and opportunities for substituting or blending mineral alkalinity into existing fill specification.
2. **Evaluate maintenance-based integration opportunities to sustain shoreline performance under sea level rise.** Assess the feasibility of incorporating alkaline sediment during planned maintenance or nourishment of living shorelines, accounting for project design lifetimes, tidal exposure, and client-specific operational constraints.
3. **Integrate carbon monitoring into living shoreline monitoring programs.** Leverage existing monitoring to track baseline carbonate chemistry in existing projects and understand how such measurements fit into existing monitoring timelines, capacity, and budget. This would be particularly useful in projects identified in Research Priority 2.
4. **Using baseline data, determine carbon uptake and potential environmental impacts in North Carolina tidal regimes.** Measure dissolution rates, alkalinity generation, and sediment stability in living shorelines across gradients of salinity, inundation frequency, and marsh vegetation common to North Carolina's estuaries. Understand the ecosystem that living shorelines support and run experiments with feedstock to examine any environmental effects.
5. **Test mineral alkalinity addition on select living shoreline features.** With appropriate baseline data and above feasibility studies, add mineral-based alkalinity to a living shoreline and follow an adequate MRV plan.

CASE STUDIES:

North Carolina

Peatland: Organic-rich wetlands that can be restored to reduce emissions and, in estuarine settings, generate/export alkalinity.

Ecosystem restoration

North Carolina has a large potential for ecosystem restoration given its vast coastal plain. An estimated one million acres of peatlands, including pocosin wetlands, can be restored,[90] and additional restoration may be possible when considering drained hydrologic restoration of agricultural lands and estuarine marsh-migration opportunity areas. The North Carolina Department of Environmental Quality (NCDEQ) has created an online mapping tool to identify wetland restoration sites (Figure 10). Ongoing restoration projects include NGO, regional, and federally funded, state-executed initiatives. In some cases, ecosystem restoration may also tie closely to the living shoreline projects described above. The larger living shoreline projects in North Carolina plant new marsh beyond sills as a part of the living shoreline. This ecosystem restoration work in North Carolina is strongly multi-benefit in nature; some projects are taken on for coastal resilience, others for water quality benefits, and some for carbon benefits.

North Carolina Coastal Wetlands Restoration Types

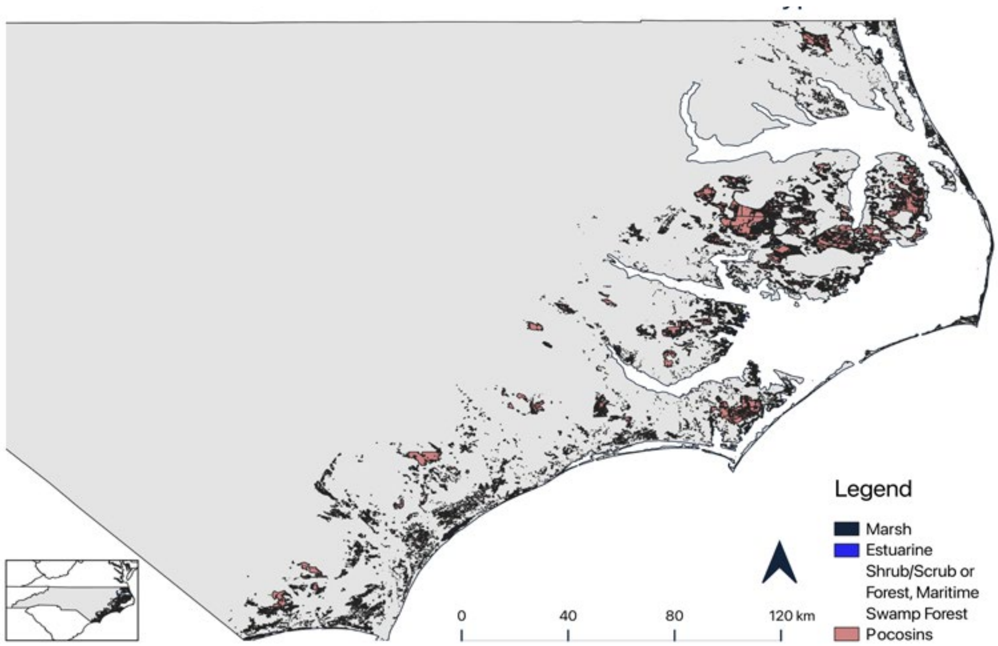


Figure 10: Subset of areas in North Carolina's coastal counties that are suitable for restoration. This figure includes marsh (salt or brackish), estuarine shrub/scrub or forest, maritime swamp forest (vegetated areas generally near high tide), and pocosins (habitats between stream divides). Full definitions of project types can be found here. Data from NCDEQ.

[90] North Carolina Natural and Working Lands Action Plan. North Carolina Department of Environmental Quality (2020). https://www.deq.nc.gov/environmental-assistance-and-customer-service/climate-change/natural-working-lands/nwl-executive-summary/download

Research priorities for integrations:

1. **Quantify alkalinity generation and carbon cycling in restored peatlands and pocosins.** Measure how rewetting of organic-rich systems influences porewater alkalinity, carbon export, and CDR under North Carolina's hydrologic conditions.

2. **Assess hydrological restoration strategies for CDR and resilience co-benefits.** Synthesize data where available to understand the effects of ditch plugging, and how water control structures and rewetting of drained agricultural lands affect carbon fluxes, soil erosion, and flooding in coastal wetlands.

3. **Evaluate targeted mineral-based alkalinity additions in organic-dominated systems.** Test through models, laboratory research, and field pilots whether limited mineral additions (e.g., TLP) can stabilize restored wetlands while boosting alkalinity generation.

4. **Integrate CDR metrics into existing restoration and monitoring frameworks.** Leverage NCDEQ mapping tools and ongoing NGO, state, and federally funded restoration monitoring to assess the current monitoring systems and where they should be strategically expanded to track abiotic mCDR.

5. **Identify priority restoration typologies for early CDR pilots in North Carolina.** Screen peatlands, pocosins, and marsh-migration zones to determine where CDR integration aligns with restoration objectives, minimizes sediment needs, and complements existing funding and permitting pathways.

Peatland in Knightdale, NC - Scott Younkin via Pexels

CASE STUDIES:

North Carolina

Natural and working lands (NWL): Managed lands (forests, farms, rangelands, wetlands) that can store carbon and deliver climate benefits.

Action plan (state climate/ resilience plan): A state-level strategy that sets goals and actions for climate mitigation/ adaptation and often guides

Enabling policies

North Carolina has a number of policies and frameworks that support successful integration of CDR into coastal resilience pathways. However, it is worth noting that almost all these initiatives have been enacted through executive order, which means subsequent elections have the potential to shift priorities or rapidly change state policy. In 2018, Executive Order 80 motivated North Carolina's Climate Risk Assessment and Resilience Plan, which included the Natural and Working Lands (NWL) Action Plan. Executive Order 305 mandates state agencies to push forward on NWL restoration and mapping. Outside of executive orders, North Carolina pursued a Wetland Program Plan n 2015 with the NCDEQ as the lead. This document, which has since been updated to cover goals for 2021–2025, was incentivized by a robust wetland research community, the desire to strengthen wetland protection goals, and alignment with federal funding at the time.

Permitting landscape

Living shorelines

Living shoreline projects in North Carolina benefit from a well-defined permitting framework administered by the Division of Coastal Management under the Coastal Area Management Act (CAMA). Most standard living shoreline designs, such as sill structures, oyster reefs, coir fiber logs, and marsh-fringe restoration, qualify for CAMA general permits, which provide expedited review and are typically issued within days when projects meet established design and siting criteria. These projects still require federal authorization, but in many cases they are covered under the USACE Nationwide Permit (NWP) 54 for Living Shorelines, allowing the agency to issue approvals quickly if the shoreline treatment stays within standard impact thresholds. More complex or site-specific designs, including projects in higher-energy settings or those requiring larger fill footprints, may need a CAMA major permit and an Individual Section 404 authorization, but early consultation with the Division of Coastal Management and use of established design templates generally shortens review cycles. The general permit structure, coordinated state–federal review, and predictable design guidance create one of the more streamlined living shoreline permitting processes on the East Coast.

General permit: A streamlined authorization for projects meeting standard criteria, avoiding full individual permit review.

Ecosystem restoration

Ecosystem restoration projects follow a coordinated permitting process involving the USACE (Section 404/Section 10), the NCDEQ, the Division of Water Resources (Section 401 Water Quality Certification), and, in the 20 coastal counties, the Division of Coastal Management under CAMA. North Carolina facilitates efficiency through a unified Pre-Construction Notification system, which allows applicants to initiate federal and state review using a single submission. Many restoration projects qualify for a NWP (e.g., NWP 27 for Aquatic Habitat Restoration), which can dramatically shorten federal review if applicants stay within footprint and impact limits. Larger or innovative restoration designs may require individual permits, but early coordination with the Division of Water Resources and the Division of Coastal Management, use of state-supported technical guidance, and clearly documented ecological benefits generally streamline review.

Nationwide Permit (NWP): USACE programmatic permits for specific activities meeting impact limits (e.g., NWP 27 restoration; NWP 54 living shorelines).

Sunset Beach, NC - Hilary Halliwell via Pexels

CASE STUDIES:

New Jersey

Weighted Score: 62

Cape May, NJ - Vlad Alexandru Popa via Pexels

Existing resilience projects

New Jersey's extensive coastline supports over seven million residents,[91] and its highly developed ocean-facing coastline makes it particularly vulnerable to flooding and inundation. In this way, New Jersey provides an example of integration opportunities in highly developed coastal regions.

Living shorelines

Over the last decade, New Jersey has embraced living shorelines, including the implementation of various projects and the creation of framework documents to increase the ease of implementation. Publicly available resources indicate 11 living shorelines in New Jersey from Upper Township to Secaucus (Figure 11), however conversations with the New Jersey Department of Environmental Protection (NJDEP) indicate a much larger number of projects. The agency notes they have **permitted over 200 nature-based solution projects with 50–60 of them meeting the definition of a living shoreline.** A new geospatial mapping tool that showcases the full scope of these projects is in development. NJDEP has commissioned and updated its Living Shorelines Engineering Guidelines.[92] Three updates to the Guidelines have been made since the original version from February 2015. The final update, which occurred in May of 2024, included the addition of other materials, such as coir mats, logs, and beach nourishment techniques, to the Guidelines as well as appendices that can aid in project design, specifically Appendix D "Engineering Design" and Appendix E "Monitoring Methodology." In 2022, the NJDEP also commissioned a Guidance and Best Practices document on developed coasts, recognizing that many of the living shorelines projects in the state are in relatively natural settings.[93] This document emphasizes that mirroring natural curvature, adding terraced structure, and increasing porosity will enhance the efficacy of living shorelines in urban environments.

[91] Coastal Zone Management Act Section 309 Program Guidance. (2025). New Jersey D

[92] Miller, J., Kerr, L., Bredes, A. & Gannon, K. Living Shorelines Engineering Guidelines - 2024 Update. https://doi.org/10.13140/RG.2.2.13319.10404 (2024).

[93] Miller, J., Kerr, L., Bredes, A. & Rella, A. Ecoshorelines on Developed Coasts Guidance and Best Practices (2022). https://www.nj.gov/dep/bcrp/docs/nj-dev-eco.pdf.

New Jersey living shorelines projects

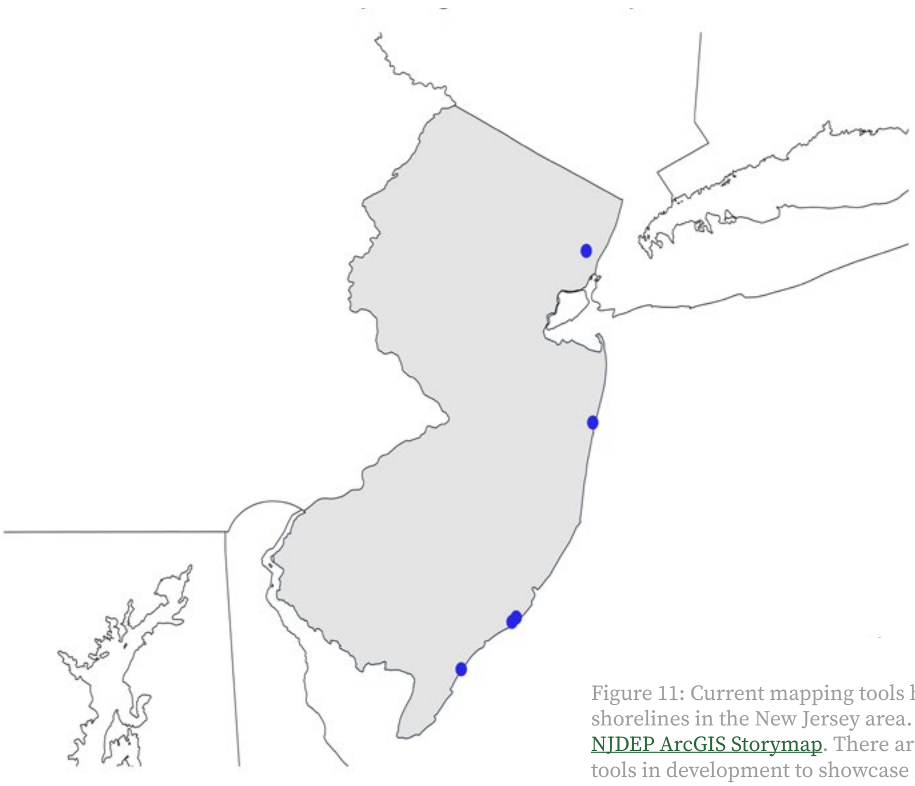


Figure 11: Current mapping tools highlight 11 living shorelines in the New Jersey area. Adapted from NJDEP ArcGIS Storymap. There are new mapping tools in development to showcase recent momentum in living shoreline projects in the state.

As the number of living shorelines in New Jersey grows, the state can serve as a hub for small-scale, mCDR integration pilot projects. These projects utilize sand and other sediment to secure their structures, grade the area, or create new habitat, which is an opportunity to incorporate alkaline material. The use of terraces and the desire for porous substrates (e.g., sand) may enhance the amount of material addition in a project. These projects may be smaller and/ or more segmented, but still provide an opportunity to increase monitoring for living shorelines. Monitoring for living shorelines, particularly innovative living shorelines in urban settings, is important, and as of 2026 is required for permits, yet interviewees highlighted that these monitoring activities are difficult to fund. As discussed in the Towards implementation section below, monitoring is a critical component of CDR projects. These small-scale integrations could drive forward monitoring for living shorelines, while building trust and refining monitoring protocols for CDR. Additionally, living shoreline projects in New Jersey are growing in scale; for example, Neptune Township, NJ is working towards constructing a living shoreline that is over 2,000 linear feet. Executing integrations at the small scale may pave the way for incorporating improved monitoring into larger projects as well.

CASE STUDIES:

New Jersey

Research priorities for integrations:

1. **Quantify material use and design-driven sediment demand in New Jersey living shorelines.** Characterize how sand, fill, and porous substrates are used across permitted New Jersey projects, including terraced designs and urban shoreline configurations outlined in NJDEP's Living Shorelines Engineering Guidelines, to identify entry points for mineral alkalinity integration.

2. **Assess mineral alkalinity compatibility with engineered and urban shoreline designs.** Through models, laboratory, and field-based experiments, evaluate how alkaline sediment performs within New Jersey-typical living shoreline elements, such as coir systems, logs, terraces, and nourishment layers, under constrained footprints and modified hydrodynamic conditions.

3. **Develop CDR-relevant monitoring approaches aligned with NJDEP permit requirements.** Since monitoring is required for New Jersey living shorelines, build on Appendix E "Monitoring Methodology" within the state's Living Shorelines Engineering Guidelines to integrate alkalinity, porewater chemistry, or carbon-relevant indicators into required living shoreline monitoring, minimizing additional burden while improving data utility.

4. **Assess CDR potential among smaller projects.** Taking the full lifetime and necessary maintenance into consideration, project the CDR uptake potential of smaller-scale, noncontinuous projects. This should include signal to noise estimates based on baseline New Jersey data as to how much mineral addition is needed to measure the alkalinity addition.

5. **Create small-scale, modular pilot designs to be used in a variety of New Jersey projects.** Plan approaches that add minerals and execute MRV suited to New Jersey's smaller, segmented living shorelines, focusing on repeatable modules that can scale across multiple sites rather than relying on large, contiguous sediment placements.

Stormwater management

In New Jersey, the main opportunities within stormwater management fall into two categories: the state-mandated green-infrastructure–first (GI-first) stormwater framework and the extensive network of stormwater basins and detention/retention systems that support both coastal and inland communities.

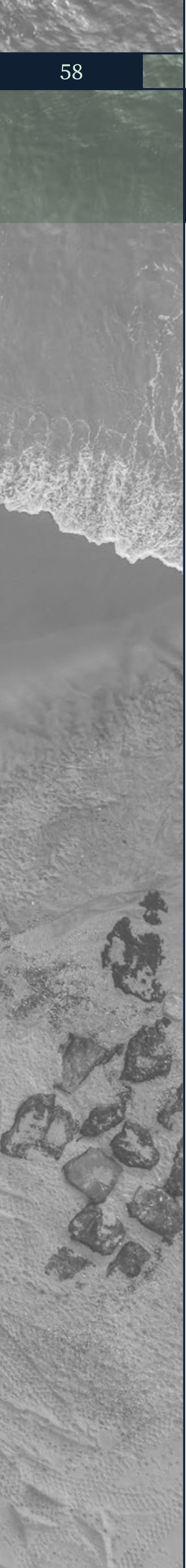
New Jersey does not have large urban combined sewer–stormwater systems statewide; instead, combined sewers are limited to a subset of older municipalities, primarily in the North Jersey urban corridor, including Newark, Paterson, Bayonne, Jersey City, Hoboken, and a small number of neighboring communities. In these systems, wet-weather flows still risk triggering CSOs during large storm events. To address this, these municipalities operate under NJDEP-approved Long-Term Control Plans (LTCP), which require evaluation of CSO control alternatives to reduce or eliminate discharge from CSO outfalls. Alternatives can include major infrastructure upgrades such as tunnel storage, expanded pump station capacity, and wet-weather treatment improvements. Many of these projects are already underway and collectively represent billions in investment aimed at reducing CSO frequency in the face of increased rainfall intensity and sea-level-driven backflow.

Outside the combined-sewer areas, New Jersey's stormwater is handled through separate municipal and private systems, as well as a very dense network of stormwater basins that number in the thousands across the state. These include infiltration basins, dry detention basins, wet ponds, and underground storage systems used in suburban development and coastal back bay communities. New Jersey's 2021 and 2023 stormwater rule updates require all major developments to meet water quality, quantity, and recharge standards using GI-first guidance. As a result, bioretention systems, infiltration structures, porous pavement, and vegetated swales are increasingly integrated into both new construction and retrofits, replacing or supplementing conventional detention-only designs.

Stormwater basin (detention/retention): Engineered storage (surface or underground) to hold, slowly release, or infiltrate runoff; candidate for alkalinity dosing.

Long-Term Control Plan (LTCP): NJDEP-approved plan for CSO communities outlining storage/treatment upgrades and timelines to reduce overflows.

Walpak Township, NJ - Shravankuman Hiregoudar via Pexels



CASE STUDIES:

New Jersey

Research priorities for integrations:

1. **Establish a cross-infrastructure baseline of stormwater chemistry and hydraulics in New Jersey.** Characterize pH, alkalinity, residence time, and flow variability across representative stormwater basins, GI-first practices, and CSO control facilities statewide to identify where alkalinity addition would be most effective and to define design envelopes for pilot CDR integrations. These studies should also identify the sources of stormwater acidity to quantify the CDR opportunity

2. **Provide a feasibility study for mineral and aqueous additions focused on New Jersey's GI-first requirements.** Quantify the extent and typologies of GI-first infrastructure in New Jersey, including bioretention and infiltration basins, and assess how alkalinity addition aligns with existing design and compliance requirements. Map potential alkalinity sources and their life cycle footprints to identify optimal feedstocks for stormwater integration.

3. **Demonstrate alkalinity addition in New Jersey-compliant stormwater practices.** Given completion of Research Priority 1, test alkalinity addition in selected stormwater or CSO-related systems across multiple storm events to evaluate dissolution performance, carbon uptake, and operational feasibility under real-world conditions.

Sunset Beach, NC - Hilary Halliwell via Pexels

4. **Develop New Jersey-specific MRV protocols that satisfy both CDR and stormwater compliance needs.** Create monitoring approaches that simultaneously support carbon accounting and NJDEP stormwater or CSO reporting requirements, reducing duplication and lowering the barrier for municipal participation.

5. **Assess regulatory thresholds and scaling constraints for alkalinity-enhanced stormwater systems in New Jersey.** Evaluate how repeated or larger-scale alkalinity additions interact with New Jersey surface and groundwater quality standards, trace metal limits, and discharge criteria to define safe operating bounds and inform pathways for scaling beyond pilots.

Asbury Park, NJ - Dark City Aerial Solutions via Pexels

Enabling policies

New Jersey has strong legislation and state-wide strategy on both coastal resilience and carbon mitigation. In 2007, New Jersey set ambitious climate targets, which also required the NJDEP to inventory greenhouse gas emissions. Then in 2021, the state put forth the New Jersey Climate Resilience Plan, which nests a Coastal Resilience Plan into one of the chapters. The plan sets major policies for the state pertaining to coastal resilience. While New Jersey does not have legislation mandating state agencies to consider carbon sequestration on their NWL, the state released a NWL Strategy in 2024 as an action under its greenhouse gas inventory mandate.

Permitting landscape

Living shorelines

Living shoreline projects in New Jersey benefit from a targeted regulatory framework designed to accelerate approval of nature-based shoreline stabilization. The NJDEP oversees coastal permitting through the Coastal Zone Management (CZM) Program. In 2013, New Jersey's CZM Rules were revised to facilitate the establishment of living shorelines. It was these revisions that modified the existing general permit for habitat creation and enhancement to allow for the construction of living shorelines in New Jersey, establishing a dedicated Living Shorelines General Permit (GP-24) to streamline implementation. GP-24 provides an efficient pathway for projects incorporating marsh sills, coir fiber structures, oyster reefs, or hybrid natural features that meet standards for ecological enhancement, minimal disturbance, and shoreline protection. This program eliminates the need for a full individual permit when applicants adhere to pre-defined design parameters. Recent permitting reform (see next paragraphs) has updated the CZM GP-24 to eliminate the project sponsorship requirement and to require monitoring post-construction.

Most recently, in 2026 New Jersey adopted its REAL (Resilient Environments and Landscapes) regulatory reforms, which are intended to address the unavoidable impacts of climate change and improve resilience throughout the state. Specifically related to living shorelines, the CZM Rules were updated to clarify that living shorelines are a type of "nature-based solution," which is a new term added to the Rules. A nature-based solution is a "project that is designed to protect, restore, or enhance shorelines, wetlands, and in-water areas utilizing natural features and processes to address erosion and flooding issues, and to restore or create ecological habitats." A new CZM General Permit 33 has been created that allows for nature-based solutions research projects.

For more complex or site-specific living shoreline designs, particularly in areas with sensitive habitat or higher hydrodynamic energy, applicants may pursue

CASE STUDIES:

New Jersey

individual permits, such as a Coastal Area Facility Review Act Individual Permit, Waterfront Development Individual Permit, and/or Coastal Wetlands Permit. Living shoreline projects, when pursued under an individual permit, generally require a combination of these available permits. Even in these cases, NJDEP's Living Shorelines Guidelines, availability of pre-application and project coordination meetings, and well-established design expectations help reduce iteration, clarify regulatory requirements, and shorten review timelines.

Stormwater management

Upgrades or modifications to existing stormwater retention and detention basins in New Jersey are permitted through NJDEP. Projects that maintain or modestly improve an existing basin's function, such as re-grading, outlet structure upgrades, or adding green infrastructure features, can potentially qualify for General Permits by Registration or General Permits by Certification, which streamline approval when standard design criteria are used. More substantial retrofits, such as converting a detention basin to infiltration or adding engineered treatment systems, can require Flood Hazard Area Control Act permits, coastal permits, freshwater wetlands permits, and often, a combination of these. The project also must demonstrate that it meets updated water quality, quantity, and recharge standards. NJDEP accelerates these reviews through standardized modeling tools, pre-application coordination, and clear design guidance for basin retrofits.

Flood Hazard Area Control Act (NJ): New Jersey regulations governing projects in flood-prone areas; often applies to basin retrofits and green infrastructure.

In combined-sewer communities, wet-weather facilities are permitted through NJDEP's LTCP framework, which serves as the umbrella authorization for storage tunnels, pump station expansions, and wet-weather treatment upgrades. Once an LTCP is approved, individual project permits are typically processed more rapidly because the underlying environmental review, hydraulic modeling, and system-wide planning have already been completed. This LTCP-based approach, paired with NJDEP's programmatic review structure, enables more efficient permitting of wet-weather infrastructure upgrades while ensuring compliance with water quality and public health requirements. CDR integrations would need to fall under these existing requirements.

Jacobi Mehringer via Pexels

Towards implementation

This roadmap illustrates, across three pathways and four states, potential integrations of CDR into coastal resilience projects. However, successful integration of CDR into a coastal resilience pathway goes beyond meeting the research priorities outlined for each case study. The first pilot projects should produce robust data on the CDR fluxes and response of the ecosystem to the project. They should follow meaningful engagement practices with local communities and rightsholders to inform project design. To ensure integrations can successfully move towards implementation, the section concludes with recommendations for various audiences.

David J Boozer via Pexels

Towards implementation

Carbon accounting and environmental responses

Meaningful engagement: Engagement that is early, transparent, resourced, culturally relevant, and enables shared decision-making and co-design. (Definition adapted from Nawaz and Belotti, 2025.)

Living shoreline,[94] ecosystem restoration,[95–97] and stormwater management [98] projects for coastal resilience implement monitoring programs often focused on storm surge conditions and other ecosystem changes to variable degrees of standardization. The monitoring, reporting, and verification (MRV) of a CDR project would add an additional layer of measurements to ensure that the activity removes carbon from the atmosphere while measuring changes in the environment to help prevent undue harm to ecosystems. In both coastal resilience and mCDR fields, environmental assessments and environmental impact statements are anticipated, particularly during the permitting process. For this implementation section, we explore environmental monitoring alongside carbon flux measurements as part of a holistic MRV plan.

Integrating CDR MRV into coastal resilience projects may enhance the ability to cross-compare resilience pathways by increasing standardization. Prior to the project start, the natural system should be monitored to understand the carbon and ecosystem baseline conditions. The system will continue to be

Veronika Andrews via Pexels

closely monitored during the CDR pilot project. The difference between the pilot project results and the baseline will be used to determine the amount of CDR for carbon quantification methods and documentation of impacts for environmental monitoring. A core challenge in MRV for integrated coastal resilience and CDR projects is additionality: determining whether observed CDR or environmental outcomes would have occurred in the absence of the project. Coastal systems are inherently dynamic and baseline conditions may shift over time, particularly where resilience interventions intentionally modify physical or ecological processes. Natural variability and existing management actions further complicate attribution. Given these complexities, assessing environmental impacts and carbon outcomes at the scale of the combined coastal resilience-mCDR intervention may be more practical than attempting to isolate individual effects.

MRV also represents a strategic opportunity for integrated coastal resilience-mCDR projects. Robust MRV builds confidence that these projects deliver credible climate benefits while remaining environmentally and socially responsible, and it provides a transparent framework for assessing outcomes that can be trusted by regulators, funders, and the public. Verified results enable comparison across approaches and, where applicable, allow CDR performance to be evaluated for participation in carbon markets. Even when projects are not designed to generate carbon credits, MRV supports assessment of cost effectiveness, including the extent to which CDR offsets emissions associated with coastal resilience construction or maintenance. Where crediting is feasible, CDR may also provide a supplemental revenue stream to support long-term project continuity or reinvestment in coastal resilience efforts. Pilot projects that may not be suitable to generate carbon credits,

Additionality: The net negativity of an intervention after factoring in lifecycle emissions and the natural carbon uptake of a system.

Carbon credits: Tradable units representing quantified CO_2 removal or avoidance; some states have looked to authorize public procurement to spur markets called purchasing programs.

[94] Morris, R. L., Pomeroy, A. W. M., Bodycomb, R. & Swearer, S. E. Building an evidence base for living shorelines: a framework for evaluating the extent and adequacy of post-establishment monitoring programs. J. Environ. Manage. 399, 128684, https://doi.org/10.1016/j.jenvman.2026.128684 (2026).

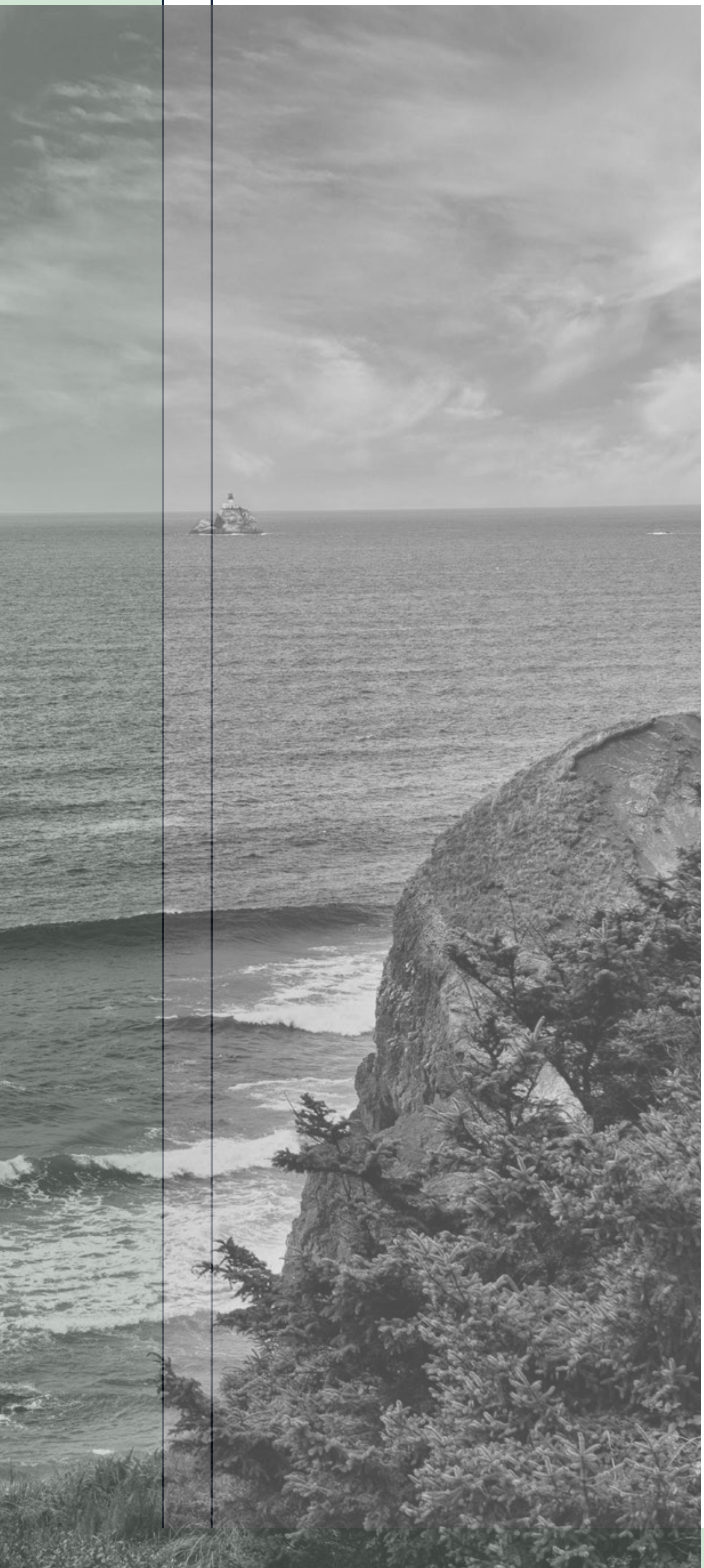
[95] Steyer, G. D. & Llewellyn, D. W. Coastal Wetlands Planning, Protection, and Restoration Act: A programmatic application of adaptive management. Ecol. Eng. 15, 385–395, https://doi.org/10.1016/S0925-8574(00)00088-4 (2000).

[96] Baldera, A., Hanson, D. A. & Kraft, B. Selecting indicators to monitor outcomes across projects and multiple restoration programs in the Gulf of Mexico. Ecol. Indic. 89, 559–571, https://doi.org/10.1016/j.ecolind.2018.01.025 (2018).

[97] Klemas, V. Using Remote Sensing to Select and Monitor Wetland Restoration Sites: An Overview, https://doi.org/10.2112/JCOASTRES-D-12-00170.1 (2013).

[98] Lee, H., Swamikannu, X., Radulescu, D., Kim, S. & Stenstrom, M. K. Design of stormwater monitoring programs. Water Res. 41, 4186–4196, https://doi.org/10.1016/j.watres.2007.05.016 (2007).

Towards implementation



due to limited scale and/or significant uncertainties in constraining carbon drawdown, are valuable research sites for fine-tuning the MRV and environmental assessment of CDR approaches. While it is beyond the scope of this roadmap to present a detailed summary of how to execute MRV and ecosystem monitoring, this section aims to provide the reader with resources to best plan the monitoring for a CDR integration into coastal resilience efforts.

MRV for integrated projects can build on existing protocols developed for specific CDR pathways (Table 1), adapting them to coastal resilience contexts. For abiotic mCDR approaches, MRV typically combines monitoring to track the application, fate, and dissolution of alkalinity addition with modeling to estimate transport, mixing, and equilibration processes that govern atmospheric CO_2 drawdown. Many coastal resilience projects already include environmental monitoring programs that can be leveraged or augmented for CDR purposes, while modeling components may require additional development due to site-specific conditions. Ongoing efforts by academic groups and third-party developers to standardize tools and methodologies may reduce costs, improve consistency, and support broader policy uptake. Regionally tailored models can improve understanding of local carbon and biogeochemical dynamics, and serve as long-term assets for coastal management and climate planning

Table 1: There are two primary mechanisms that increase alkalinity to support coastal resilience and draw down carbon: mineral or aqueous addition. For mineral-based addition, we find that existing enhanced weathering and ocean alkalinity enhancement frameworks are likely to be most useful. For aqueous additions, ocean alkalinity enhancement frameworks are likely to be most useful. Below, we have organized resources on these pathways, as well as current carbon accounting and ecosystem monitoring approaches. As the field evolves, more specific methodologies for coastal resilience CDR integrations may be needed.

Relevant CDR Approach	Coastal Resilience Pathway for CDR Integration	MRV Reviews and Protocols	Ecosystem Monitoring Tools
Enhanced Weathering	Living Shorelines: Dune Ecosystem Restoration: TLP	Clarkson et al, 2024,[99] A review of measurement for quantification of carbon dioxide removal by enhanced weathering in soil Cascade Climate, Foundations for CDR Quantification in Enhanced Rock Weathering Deployments Isometric, Enhanced Rock Weathering Protocol Puro.earth, Geologically Enhanced Weathering; Rainbow, Enhanced Rock Weathering	Levy et al., 2024,[100] Enhanced Rock Weathering for CDR–Monitoring and Mitigating Potential Environmental Impacts on Agricultural Land
Ocean Alkalinity Enhancement	Living Shorelines: Tidal Ecosystem Restoration: General Stormwater Management	Fennel et al., 2025,[101] The Verification Challenge of Marine Carbon Dioxide Removal Isometric, Ocean Alkalinity Enhancement from Coastal Outfalls Isometric, Wastewater Alkalinity Enhancement River Alkalinity Enhancement	Fawcett et al., 2025, Ocean Alkalinity Enhancement (OAE) Environmental Impact Monitoring Framework (in review) Hourglass Climate,[102] Framework for Ecotoxicological Modeling of mCDR, 2026

Ocean alkalinity enhancement (OAE): Directly increasing seawater alkalinity (e.g., mineral or liquid alkalinity addition) to enhance CO_2 uptake and storage.

Enhanced weathering: Spreading and breakdown of finely ground minerals (often on land) to increase alkalinity delivered to waters and drive CO_2 uptake.

[99] Clarkson, M. O. et al. A review of measurement for quantification of carbon dioxide removal by enhanced weathering in soil. Front. Clim. 6, 1345224, https://doi.org/10.3389/fclim.2024.1345224 (2024).
[100] Levy, C. R. et al. Enhanced Rock Weathering for Carbon Removal–Monitoring and Mitigating Potential Environmental Impacts on Agricultural Land. Environ. Sci. Technol. 58, 17215–17226, https://doi.org/10.1021/acs.est.4c02368 (2024).
[101] Fennel, K. The Verification Challenge of Marine Carbon Dioxide Removal. Annu. Rev. Mar. Sci. 18, 141–164, https://doi.org/10.1146/annurev-marine-032123-025717 (2026).
[102] Weighman, K., Jankowska, E., Andrews, M. G. Framework for Ecotoxicological Modeling of mCDR (FEMM) v1.0, https://zenodo.org/records/18487758 (2026).

CDR should reinforce environmental justice

Environmental justice: Fair treatment and meaningful involvement of all people, especially historically marginalized communities, in environmental decisions.

Effective integration of coastal CDR strategies into coastal resilience infrastructure depends on early, consistent, and community-first engagement to address environmental justice considerations. Across practitioner guidance,[103] community listening sessions, and Indigenous knowledge frameworks,[104] cross-cutting insights clarify how to align CDR with coastal resilience in a just and responsible way. While this roadmap summarizes best practices, each location (state and municipality) will have a different social context. Legacies or past harm, wrongdoing, and other environmental justice considerations will vary across localities which will in turn affect the level of trust, interest in engaging, and who may serve as trusted actors and/or institutions. In this roadmap, environmental justice considerations were not included within the enabling criteria to determine the case studies. Engagement and the policy that enables community engagement will need to be adaptive to these social differences.

Begin engagement early and center community priorities

Successful CDR pilot projects require building understanding before proposing field trials. Projects are most successful and equitably implemented when engagement is proactive, transparent, and rooted in local priorities rather

than project timelines. Early conversations allow communities to articulate concerns, desired benefits, and conditions for support, while reducing surprise and distrust. The how-to guide on Engaging Coastal Communities on Ocean Alkalinity Enhancement stresses that early-stage dialogue helps communities grasp the purpose, scale, and potential impacts of CDR, forming the basis for shared decision-making.[103] Meaningful community engagement is also likely to enhance the project by incorporating regional knowledge that may be critical to project success.

Co-develop CDR with communities

Communities are more supportive of CDR if projects directly address local environmental burdens, provide durable community benefits, and align with broader resilience goals. The National Wildlife Federation's community listening sessions found strong concern that carbon management could perpetuate historic inequities unless benefits are concrete, enforceable, and co-designed with residents, such as targeted job pathways, transparent and accessible environmental monitoring access, and improvements to local infrastructure or habitat health. Coastal CDR must contribute to regenerative outcomes rather than reproduce extractive patterns.

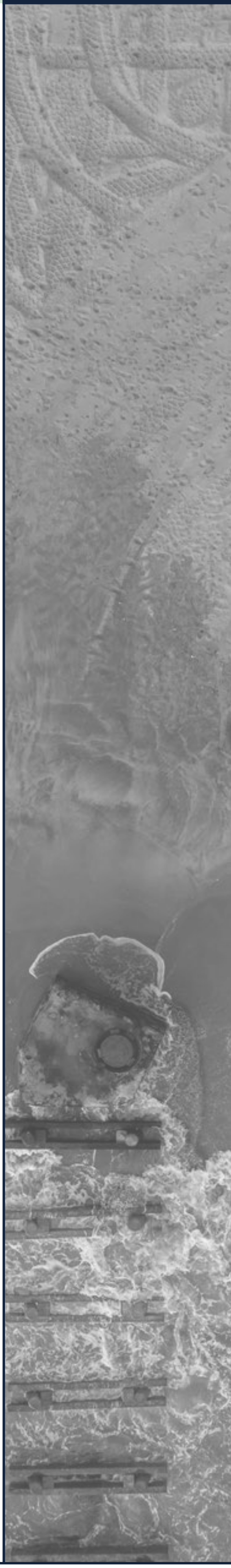
Community benefits: Concrete, co-designed outcomes (e.g., jobs, monitoring access, habitat improvements) that address local priorities and inequities.

Across all available sources on community engagement, the overarching message is clear: coastal CDR must be built with communities, not for them. A successful coastal resilience CDR integration positions community knowledge and local priorities as foundational, particularly in locations where there is a history of environmental injustice. Engagement that is early, transparent, participatory, and justice centered creates the social license and shared stewardship needed for CDR to strengthen coastal resilience.

Build trust through transparency and independent communication

Trust is a major barrier to CDR, particularly in places with a legacy of environmental harm and industry exploitation. Listening sessions in Louisiana found that communities want clear, unbiased explanations of risks, monitoring, siting, regulatory oversight, and long-term safety delivered by trusted, independent messengers, not industry representatives. Transparent communication about uncertainties and impacts throughout the technology lifecycle, including upstream effects and how the supply chain may influence communities, strengthens credibility and helps communities assess whether CDR aligns with their environmental and social priorities.

[103] Nawaz, S. & Belotti, G. Engaging Coastal Communities on Ocean Alkalinity Enhancement: A How-to Best Practice Guide. 40 (2025).
[104] Gardner, L., Hogg, V. & Aristi, K. Informing Marine Carbon Dioxide Removal: Best Practices Guidance for Tribal and Indigenous Engagement.



Charrette (engagement): Intensive, collaborative design workshop used to co-develop project options with stakeholders.

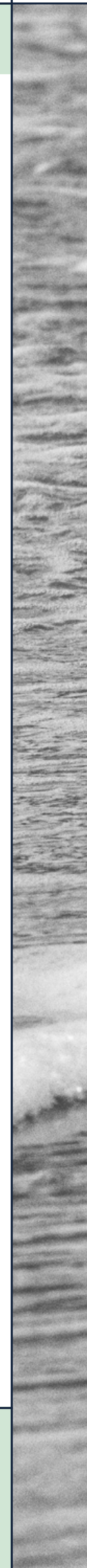
Free, prior, and informed consent (FPIC): Rights-based standard requiring Indigenous consent before actions affecting their lands/waters/rights.

Use interactive, participatory, and culturally relevant engagement methods

One-way information sharing is insufficient. The Engaging Coastal Communities in Ocean Alkalinity Enhancement guide highlights interactive methods of community engagement such as scenario planning, mapping, storytelling, and charrettes that allow residents to consider trade-offs, reflect on local ecological knowledge, and collaboratively envision desired futures.[103] These approaches also create space for community members to raise localized concerns related to fisheries, water quality, coastal heritage, and climate impacts. To best reach a full community, and keep invested users and rightholders involved in the project evolution, engagement must be iterative throughout project design and execution, not a single meeting. Offer community members leadership and decision-making roles whenever possible. These engagements must consider accessibility for the invested community including, but not limited to, scheduling in accessible hours, hosting events in accessible locations (e.g., close to public transit) and ensuring a means of compensation. Community-based organizations can help ensure appropriate engagement methods are utilized.

Indigenous community engagement requires distinct, rights-based partnership

Where Indigenous nations are present, engagement must be grounded in sovereignty, free, prior, and informed consent (FPIC), and long-term relationship building.[105] Indigenous communities are rights holders, not just invested community members.[106] Indigenous communities should be included at the onset of project design to shape engagement priorities, methodologies, research questions, and knowledge-sharing protocols.[103,107] Respect for Indigenous science, governance systems, cultural values, data sovereignty, and established research agreements is essential for any responsible CDR effort. CDR strategies must complement ongoing Indigenous stewardship of marine ecosystems.



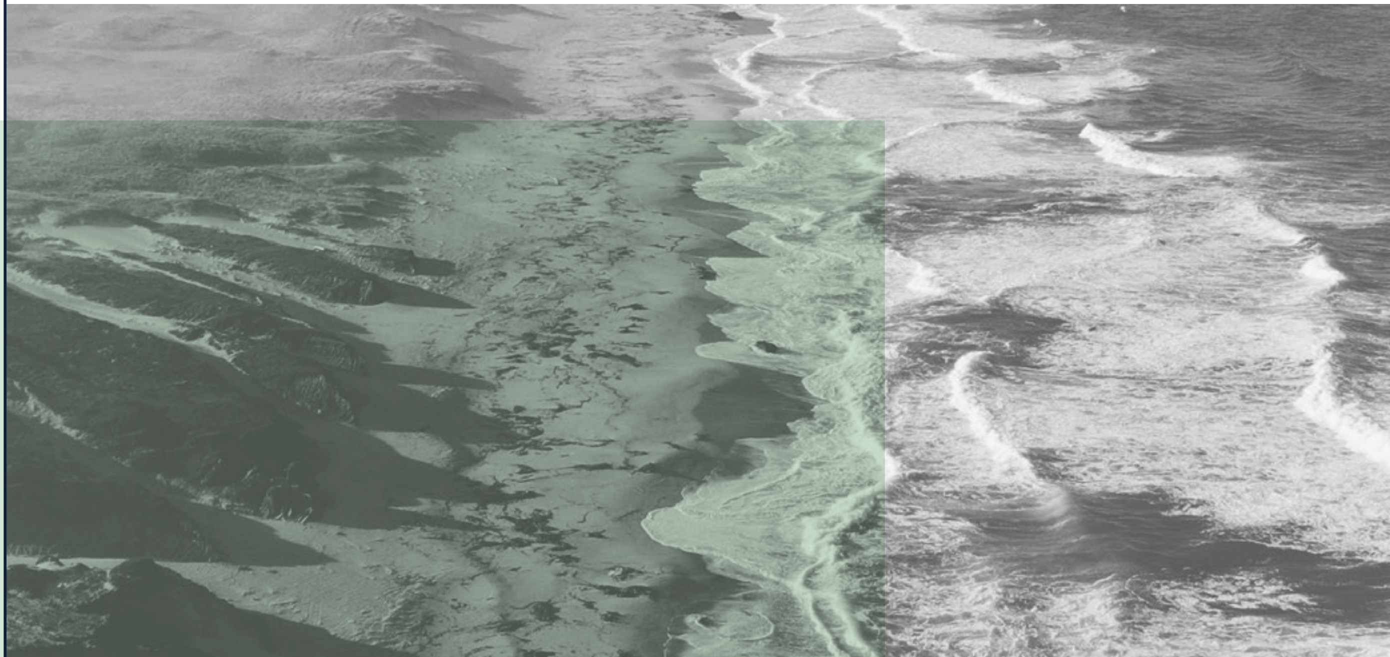
[105] UNDRIP. United Nations Declaration on the Rights of Indigenous Peoples: Resolution / Adopted by the UN General Assembly. (2007).
[106] Bull, J. et al. Shifting practice: recognizing Indigenous rights holders in research ethics review. Qual. Res. Organ. Manag. Int. J. 15, 21–35, https://doi.org/10.1108/QROM-04-2019-174 (2019).
[107] Grabb, K. C. et al. The importance of engagement with fisheries, aquaculture, and Indigenous communities in the planning and implementation of marine carbon dioxide removal (mCDR). ICES J. Mar. Sci. 82, fsaf198, https://doi.org/10.1093/icesjms/fsaf198 (2025).

Recommendations for next steps

The analysis in this roadmap has shown that integrating abiotic mCDR into coastal resilience projects is both technically plausible and institutionally feasible. However, no single actor can advance this work alone. This roadmap is targeted at a number of audiences, each that have tools at their disposal to move this from concept into practice.

For policymakers, the findings highlight where statutory authority, durable funding, and clear state planning can unlock dual-benefit projects that support communities. For state research and regulatory agencies, the roadmap offers a lens to incorporate CDR pilot projects into existing planning, permitting, and project delivery. For those that work in the CDR space, such as researchers, invested communities and rightsholders, and industry actors, this product identifies realistic integration points, monitoring needs, and governance expectations that should shape technical research and implementation strategies. For the coastal resilience space, including engineers, planners, Tribal nations, and local governments, the roadmap illustrates how emerging CDR pathways can strengthen core resilience goals when designed with ecological and community outcomes at their center.

The following recommendations translate these insights into near-team, role-specific actions. They are not exhaustive, but they provide a practical starting point for each audience to advance accountable, practice-driven integration of mCDR into coastal resilience.



A) Federal, state, and local policymakers

1. **Create incentives for dual-benefit projects.** To start, include CDR solutions among approaches eligible for resilience and adaptation funding. As lab and pilot projects present general evidence for larger scale projects, offer competitive advantage or matching funds to coastal resilience projects with integrations.

2. **Safeguard carbon mitigation initiatives.** Convert executive order–based carbon mitigation and net-zero commitments into statute by assembling broad coalitions that emphasize co-benefits such as economic development, resilience, and public health.

3. **Create requirements for engagement with communities (particularly those marginalized by past harms), environmental justice groups, and Indigenous rightsholders.** Tie early project components (e.g., state funding or permitting approval) to the demonstration of FPIC processes, locally co-developed engagement plans, and transparent communication practices.

B) State agencies

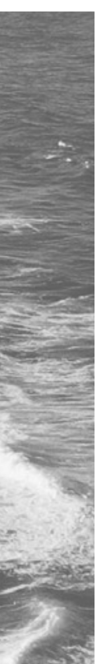
1. **Create a centralized coastal sediment and material registry.** In coordination with federal agencies, track sediment sourcing, dredge reuse, and potential alkaline substrate availability so engineers and CDR developers can easily assess feasibility and regulators can best assess cumulative project risk versus benefit.

2. **Create a centralized stormwater management system registry.** In coordination with municipalities, track both gray and green stormwater infrastructure projects, including water storage capacity and utilization rates, in order for engineers and CDR developers to assess feasibility.

3. **Incentivize innovative, community-aligned carbon mitigation within coastal projects.** Add carbon-benefit scoring and justice-centered engagement review criteria to state funding competitions, with external technical and social science reviewers.

4. **Provide engagement support infrastructure.** Fund information and institutional infrastructure (e.g., content creation, translation services, and physical meeting spaces) along with independent facilitators, community liaisons, and interpreters to support transparent, culturally relevant, and locally trusted engagement processes.

5. **Identify regulatory experts.** Understand who would be well positioned to oversee regulatory processes on CDR integrations within coastal resilience workflows.



Kyle Collins via Pexels

Recommendations for next steps

C) CDR field

(industry and researchers)

1. **Build strong partnerships with coastal resilience practitioners.** Co-create working groups with engineers, planners, Tribal nations, and local governments to identify integration opportunities early. Fund long-term partnership-focused positions.

1. **Develop technical guidance for CDR-compatible coastal design.** Produce clear engineering guidance (e.g., dosing rates, substrate standards, monitoring requirements, cumulative impacts) and ensure it reflects community and Indigenous priorities.

2. **Follow data best practices.** Utilize existing data management protocols and share data early and often to establish trust and transparency. Partner with government and academic researchers.

D) Coastal resilience field

(industry and researchers)

1. **Integrate CDR feasibility into early-stage project scoping.** Especially in pilot or research motivated projects, include carbon removal potential, financial opportunities and constraints, substrate suitability, and monitoring capacity into conceptual design stages rather than late in the engineering process.

2. **Collaborate with CDR developers on mutual-benefit pilots.** When integrating CDR into the pathways examined in this roadmap, bring CDR practitioners into the monitoring plan and design phases to ensure robust accounting and ecosystem monitoring.

E) Climate and environmental NGOs

1. **Co-develop and execute pilot projects.** Identify a pilot for each integration pathway and pursue them through multi-sector collaboration. Share data, including null results, transparently with invested and Indigenous communities.

2. **Understand potential scale and limits.** Conduct feasibility assessments on maximum CDR potential under ecological, hydrological, and cultural constraints.

3. **Implement meaningful community and Indigenous engagement as a requirement, not a parallel track, with particular focus on marginalized groups.** Begin engagement early and co-design the process with community

partners. Require continuation of engagement after approval, including regular reporting of results and outcomes. Use independent facilitators and culturally relevant methods. Incorporate Indigenous governance, FPIC, and knowledge systems into decision-making. Ensure communities help shape project purpose, monitoring, benefits, and safeguards.

F) Catalytic funders

1. **Fund early-stage integrations, pilots, and outlined research priorities.** Support feasibility studies, demonstration projects, and first-of-a-kind deployments that test how CDR can be responsibly integrated into coastal resilience efforts. Early philanthropic investment reduces uncertainty and enables public agencies and private funders to scale proven approaches.
2. **Invest in coordination and shared infrastructure.** Resource cross-sector convenings, data platforms, and long-term partnerships that align engineers, policymakers, researchers, and communities. These investments reduce fragmentation, speed up learning, and create common standards for design, monitoring, and governance.
3. **Resource meaningful invested and Indigenous community engagement.** Fund engagement as core project infrastructure, not an add on, by supporting independent facilitators, community liaisons, and long-term relationship building. Early and sustained investment in engagement builds trust, improves project design, and strengthens long-term durability and legitimacy.

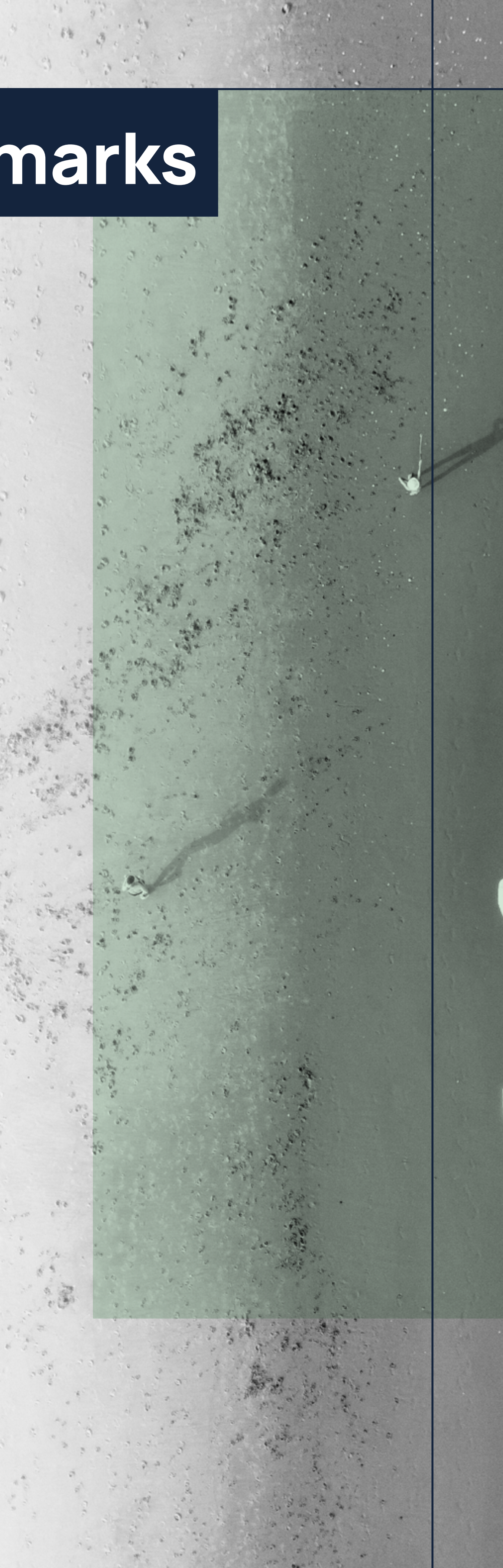
Taken together, these recommendations direct a collaborative pathway for piloting CDR within coastal resilience infrastructure. Early projects will be modest in scale, as they have been in both fields to date. Even so, they can deliver clear value to clarify monitoring approaches, refine permitting expectations, develop community engagement models, and build a shared body of evidence on environmental performance.

Jacobi Mehringer via Pexels

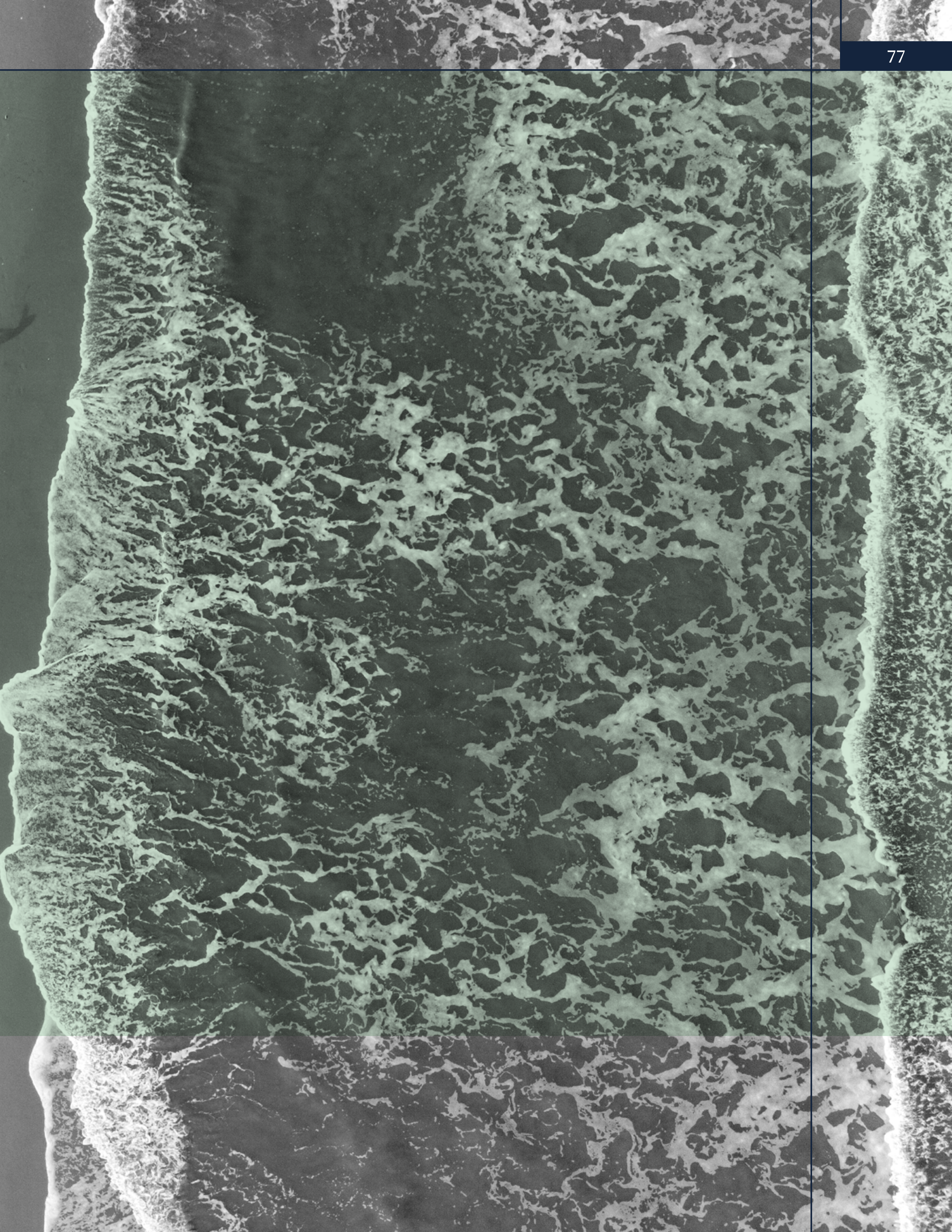
Concluding remarks

This roadmap demonstrates how integrating abiotic mCDR into coastal resilience projects is a practical extension of public benefit work underway across the United States. Living shorelines, ecosystem restoration, and stormwater management infrastructure have permitting, maintenance, and monitoring that align closely with CDR projects needs. These integrations are highlighted in four case studies in U.S. coastal states to examine the physical integrations, as well as policies that could enable their implementation. **The desire to execute projects quickly is felt from both fields given that coastal communities are already living with the impacts from sea-level rise, compound flooding, and erosion as carbon pollution continues to grow.** Early projects must prioritize close coordination with permitting agencies, robust MRV, and sustained community engagement. If these scientifically grounded projects move forward in a way that is guided by communities and aligned with resilience priorities, embedded CDR can help ensure that investments in coastal protection contribute meaningfully to long-term climate mitigation.

Realizing the potential of this integrated approach will require sustained coordination and learning across disciplines. **This roadmap is a practical starting point for policymakers, agencies, practitioners, communities, and funders who are interested in building coastal projects that maximize public benefit.** In treating coastal resilience investments as opportunities to pilot CDR, including sharing results openly and adjusting for a growing evidence base, a joint effort can build a clear foundation for how these approaches can contribute to the future of coastal management.



Kelly via Pexels



Appendix

Appendix A: Determination of Case Study Locations

In order to narrow in on case studies for this roadmap that would highlight novel integration opportunities and present strong enabling conditions for integrations, we developed a weighted criteria approach. The weighting scheme was developed based on qualitative information provided by the 40 interviews conducted for this project, but the weighted criteria were developed from researched sources discussed in more details below. The weighting process used a linear scale of 1–15, whereby 15 indicates the most influential criteria (Table A1). Interview feedback consistently emphasized that policy and regulatory conditions, such as permitting pathways, interagency coordination, and alignment with existing programs, often represent the primary constraints on implementation, particularly for innovative or cross-sector projects. Accordingly, policy-focused criteria were weighted more heavily to capture their outsized influence on project viability, with the expectation of federal funding. Billion-dollar disaster events were elevated in the weighting scheme because of their ability to indicate coastal hazard risk. The use of a unique, linear ranking system makes these tradeoffs explicit and avoids ties among criteria; higher-ranked criteria indicate greater relative influence on implementation feasibility, not greater intrinsic importance.

Table A1: The final rank list that was used to weight the criterion. This is a unique ranking system where a higher rank is weighted as a more important criterion. The rank list was constructed based on information gathered from expert opinion provided during the interview process and, therefore, is intended to capture real-world enabling conditions of successful coastal resilience projects. Colors correspond to the group of the criterion, where blue is economic and geographic, yellow is policy, and green is need and capacity.

Criterion	Weight
Regulatory Coordination	15
Regulatory Ease	14
Natural and Working Lands Policy	13
State-wide Coastal Resilience Action Plan	12
Net Zero Policy	11
Billion-dollar Disasters since 2018 (Normalized)	10
State Funding (Normalized)	9
Coastal Institutions (Normalized)	8
Project Score	7
Coastal GDP (Normalized)	6
Federal Funding since 2023 (Normalized)	5
Coastal Population (Normalized)	4
Coastline (Normalized)	3
Number of Ports (Normalized)	2
Number of National Estuarine Research Reserve (Normalized)	1

Table A2: This table includes the final scores that were used to determine case studies. We considered all coastal US states, excluding the Great Lakes. 100 is the highest possible score and 0 is the lowest for enabling conditions. The top-ranked states that are utilized as case studies in this roadmap are bolded.

State	Final Ranked Score
Louisiana	78.1
California	77.7
North Carolina	63.5
New Jersey	61.7
Texas	61.1
Florida	58.8
Oregon	57.4
New York	57.4
Connecticut	56.9
Maryland	56.7
Virginia	54.8
Delaware	52.5
Washington	50.9
Massachusetts	50.1
New Hampshire	48.5
Maine	48.0
Georgia	44.8
Rhode Island	43.4
South Carolina	38.4
Mississippi	37.4
Alabama	31.8
Hawaii	31.5
Alaska	20.3

Here we discuss the criteria that went with the weighting scheme (Table A1) to determine the ranked list of states (Table A2). The economic and geographic criteria (amount of coastline in miles, coastal population, GDP, are from NOAA CZMA[1] and number of ports from NOAA OceanReports Tool. Policy-relevant criteria (net-zero goals, resilience action plans, regulatory ease, regulatory coordination, natural and working lands (NWL) policy, number of projects, state funding, federal funding) were largely pulled from the Georgetown Climate Center's Adaptation Clearinghouse as well as interview and research data on state policies, regulatory processes, and funding. Billion dollar disaster and National Estuarine Reserve (NERR) data are from NOAA CZMA.[1] Coastal institutions were compiled via independent research. Given the large range in some of the values, the data were normalized to a value from 0 to 1 (Table A2) in order to be evaluated in the weighting scheme. Raw values utilized are also reported (Table A3). Raw values that fall in the range of 0–1 are explained in the caption of Table A4.

Appendix

Table A3: Criteria values utilized for each state used to create the state scores out of 100. Values with _norm were normalized to a value from 0 to 1.

State	Final Ranked Score	Regulatory Coordination	Regulatory Ease	Natural and Working Lands Policy	Resilience Action Plan	Net Zero Policy	Billion-dollar Disasters since 2018 (Normalized)	State funding (Normalized)	Coastal Institutions (Normalized	Projects Score	Coastal GDP (Normalized)	Federal Funding since 2023 (normalized)	Coastal Population (Normalized)	Coastline Length (Normalized)	Number of Ports (Normalized)	Number of National Estuarine Research Reserve (Normalized)
Louisiana	78.1	1.0	1.0	1.0	1.0	1.0	0.5	1.0	0.2	1.0	0.2	0.6	0.1	0.2	0.5	0.0
California	77.7	1.0	0.5	1.0	1.0	1.0	0.2	0.1	1.0	1.0	0.9	1.0	1.0	0.1	0.9	1.0
North Carolina	63.5	1.0	0.5	1.0	1.0	0.5	0.6	0.0	0.2	1.0	0.0	0.2	0.0	0.1	0.1	0.3
New Jersey	61.7	1.0	1.0	0.5	1.0	1.0	0.3	0.0	0.1	1.0	0.2	0.3	0.3	0.0	0.1	0.3
Texas	61.1	1.0	1.0	0.5	1.0	0.0	1.0	0.0	0.3	0.5	1.0	0.1	0.2	0.1	0.6	1.0
Florida	58.8	1.0	0.5	0.5	1.0	0.0	0.4	0.1	0.8	1.0	0.6	0.4	0.6	0.2	1.0	0.3
Oregon	57.4	1.0	1.0	1.0	1.0	0.5	0.2	0.0	0.2	0.5	0.0	0.4	0.0	0.0	0.2	0.3
New York	57.4	0.0	0.5	1.0	1.0	1.0	0.4	0.1	0.6	1.0	0.4	0.6	0.6	0.1	0.3	0.3
Connecticut	56.9	1.0	1.0	1.0	1.0	0.5	0.2	0.0	0.1	0.5	0.1	0.2	0.1	0.0	0.2	0.3
Maryland	56.7	0.5	0.5	1.0	1.0	1.0	0.4	0.0	0.2	1.0	0.2	0.5	0.1	0.1	0.0	0.3
Virginia	54.8	1.0	0.5	0.5	1.0	0.5	0.6	0.0	0.2	1.0	0.2	0.5	0.2	0.1	0.0	0.3
Delaware	52.5	1.0	0.5	1.0	1.0	1.0	0.1	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.3
Washington	50.9	0.0	1.0	0.5	1.0	1.0	0.2	0.0	0.4	1.0	0.3	0.4	0.2	0.1	0.5	0.3
Massachusetts	50.1	0.0	0.5	1.0	1.0	1.0	0.2	0.0	0.6	1.0	0.1	0.2	0.2	0.0	0.2	0.3
New Hampshire	48.5	1.0	1.0	0.5	1.0	0.5	0.1	0.0	0.0	0.5	0.0	0.2	0.0	0.0	0.0	0.3
Maine	48.0	0.0	1.0	1.0	1.0	1.0	0.0	0.0	0.2	0.5	0.0	0.1	0.0	0.1	0.2	0.3
Georgia	44.8	1.0	1.0	1.0	0.5	0.0	0.7	0.0	0.1	0.5	0.0	0.1	0.0	0.1	0.1	0.3
Rhode Island	43.4	1.0	0.0	0.5	1.0	1.0	0.1	0.0	0.2	0.5	0.0	0.0	0.0	0.0	0.1	0.3
South Carolina	38.4	1.0	0.5	0.5	0.5	0.0	0.5	0.0	0.1	0.5	0.1	0.2	0.0	0.1	0.1	0.7
Mississippi	37.4	1.0	1.0	0.0	0.5	0.0	0.5	0.0	0.1	0.5	0.0	0.0	0.0	0.0	0.1	0.3
Alabama	31.8	0.5	1.0	0.5	0.0	0.0	0.5	0.0	0.1	0.5	0.0	0.0	0.0	0.0	0.0	0.3
Hawaii	31.5	0.0	0.0	1.0	0.5	1.0	0.0	0.0	0.1	0.5	0.1	0.3	0.0	0.0	0.3	0.3
Alaska	20.3	0.0	0.0	0.5	0.5	0.0	0.0	0.0	0.2	0.5	0.1	0.3	0.0	1.0	0.6	0.3

Appendix

Table A4: Criteria raw values were assigned to each state based on research conducted for this roadmap. Policy-related criteria, including net-zero goals, coastal resilience action plans, and NWL policy, were scored from 0 to 1, where 0 indicates no policy or plan, 0.5 indicates an executive order or related initiatives without a formal policy, and 1 indicates a policy in place. Regulatory ease reflects the accessibility of permitting information, with 0 indicating no centralized or streamlined information, 0.5 indicating partial accessibility or fragmented processes, and 1 indicating a centralized coastal permitting information source. Regulatory coordination reflects agency roles and intergovernmental coordination, with 0 indicating limited involvement or coordination, 0.5 indicating some coordination without administration of federal consistency, and 1 indicating strong coordination by state administration with the federal process. The number of coastal resilience projects was scored from 0 to 1 due to fragmented public data, where 0 indicates limited projects, 0.5 indicates fewer than 100 projects, and 1 indicates more than 100 projects statewide.

State	Final Ranked Score	Regulatory Coordination	Regulatory Ease	Natural and Working Lands Policy	Coastal Resilience Action Plan	Net Zero Policy	Billion-dollar Disasters since 2018	State funding in resilience per year (millions, since consistent line items)	Number of Coastal Institutions	Projects Score	Coastal GDP (billions of usd)	Federal Funding since 2023 (Millions)	Coastal Population	Coastline Length (Miles)	Number of Major Ports	Number of National Estuarine Research Reserve
Louisiana	78.1	1.0	1.0	1.0	1.0	1.0	31	$1,750	3	1.0	$8.7	22,186,800	2,378,000	7,721	6	0
California	77.7	1.0	0.5	1.0	1.0	1.0	11	$220	10	1.0	$41.9	5,924,507	26,779,000	3,427	11	3
North Carolina	63.5	1.0	0.5	1.0	1.0	0.5	36	$14	3	1.0	$2.9	6,297,008	1,267,000	3,375	2	1
New Jersey	61.7	1.0	1.0	0.5	1.0	1.0	21	$25	2	1.0	$11.1	9,200,837	7,150,000	1,792	2	1
Texas	61.1	1.0	1.0	0.5	1.0	0.0	61	$33.35	4	0.5	$46.6	4,708,800	6,865,900	3,359	8	1
Florida	58.8	1.0	0.5	0.5	1.0	0.0	25	$150	8	1.0	$30.1	15,108,675	16,236,190	8,436	12	3
Oregon	58.1	1.0	1.0	1.0	1.0	0.5	11	$7	3	0.5	$2.7	15,937,565	690,600	1,410	3	1
New York	57.4	0.0	0.5	1.0	1.0	1.0	26	$220	6	1.0	$21.2	22,383,400	15,900,000	2,625	4	1
Connecticut	56.9	1.0	1.0	1.0	1.0	0.5	12	$5.5	2	0.5	$4.8	8,176,800	2,230,000	618	3	1
Maryland	56.7	0.5	0.5	1.0	1.0	1.0	26	$15	3	1.0	$9.4	16,400,028	4,315,000	3,190	1	1
Virginia	54.8	1.0	0.5	0.5	1.0	0.5	38	$50	3	1.0	$9	16,337,018	5,068,200	3,315	1	1
Delaware	52.5	1.0	0.5	1.0	1.0	1.0	7	$7	1	0.5	$1.4	273,300	967,700	381	1	1
Washington	50.9	0.0	1.0	0.5	1.0	1.0	10	10	5	1.0	$12.7	13,095,841	5,209,000	3,026	6	1
Massachusetts	50.1	0.0	0.5	1.0	1.0	1.0	14	$29	6	1.0	$7.4	7,378,890	5,222,000	1,519	3	1
New Hampshire	48.5	1.0	1.0	0.5	1.0	0.5	4	$3	1	0.5	$1.7	6,162,622	438,400	131	1	1
Maine	48.0	0.0	1.0	1.0	1.0	1.0	3	$5	3	0.5	$2.7	5,526,580	736,500	3,478	3	1
Georgia	44.8	1.0	1.0	1.0	0.5	0.0	42	$0	2	0.5	$1.6	2,233,175	605,100	2,344	2	1
Rhode Island	43.4	1.0	0.0	0.5	1.0	1.0	9	$6	3	0.5	$2.5	1,477,759	1,057,800	384	2	1
South Carolina	38.4	1.0	0.5	0.5	0.5	0.0	30	$6	2	0.5	$4.2	5,646,221	1,473,500	2,876	2	2
Mississippi	37.4	1.0	1.0	0.0	0.5	0.0	29	$20	2	0.5	$2.2	1,029,830	396,500	359	2	1
Alabama	31.8	0.5	1.0	0.5	0.0	0.0	31	$21.8	2	0.5	$1.9	1,958,800	632,300	607	1	1
Hawaii	31.5	0.0	0.0	1.0	0.5	1.0	1	$6.5	2	0.5	$6.4	11,444,961	1,420,000	1,052	4	1
Alaska	20.3	0.0	0.0	0.5	0.5	0.0	2	$0	3	0.5	$5.1	9,449,183	606,100	33,904	8	1

Appendix

Appendix B: Glossary of Terms

This glossary describes the jargon used in this report. It includes both the traditional definition and, where appropriate, highlights the context in which it is used in this roadmap.

Abiotic mCDR:
Approaches that rely on chemical/physical processes (e.g., alkalinity addition, direct ocean capture) to draw down CO_2.

Action plan (state climate/ resilience plan):
A state-level strategy that sets goals and actions for climate mitigation/adaptation and often guides funding and permitting.

Additionality:
The net negativity of an intervention after factoring in lifecycle emissions and the natural carbon uptake of a system.

Alkalinity:
Water's capacity to neutralize acids, largely controlling ocean pH buffering; raising alkalinity generally enhances seawater CO_2 uptake.

Baseline (for MRV):
Pre-project measurement of carbon, ecosystem, and social conditions used to compare against pilot results to quantify net change.

Beneficial use of dredged sediment: Placing dredged material to restore habitats, nourish beaches/dunes, or support resilience features, rather than disposing offshore.

Biotic mCDR:
CO_2 removal pathways that rely on living organisms (e.g., seaweed cultivation and sinking or nutrient fertilization) to take up and lock away carbon from the atmosphere.

Blue carbon:
Carbon captured and stored in coastal vegetated habitats (salt marshes, mangroves, seagrass) via organic matter accumulation.

Billion-Dollar Disaster (NOAA):
A U.S. weather/climate event with damages ≥ $1 billion, used as an indicator of risk and adaptation needs.

Bioswale / vegetated swale:
Shallow, vegetated channels that slow, infiltrate, and filter stormwater (a green-infrastructure practice).

Carbon accounting:
Quantifying CO_2 removed (and related emissions/impacts) using standardized methods as part of MRV.

Carbon credits:
Tradable units representing quantified CO_2 removal or avoidance; some states have looked to authorize public procurement to spur markets called purchasing programs.

Carbon dioxide removal (CDR): Activities that remove CO_2 from the atmosphere and store it for long periods (ideally ≥ 1,000 years).

Carbon sequestration:
The storage phase of CDR, largely referring to retaining CO2 as organic carbon, like biomass and soils.

Charrette (engagement):
Intensive, collaborative design workshop used to co-develop project options with stakeholders.

Clean Water Act (CWA) Sections 401/404:
U.S. water quality certifications (401) and permits for discharge of dredged/fill material (404) administered by USACE/states.

Coastal resilience:
The capacity of coastal ecosystems, economies, and communities to withstand, adapt to, and recover from coastal hazards.

Combined sewer overflow (CSO): Discharge events when combined sewer–stormwater systems exceed capacity during storms and release untreated/wet-weather flows.

Community benefits:
Concrete, co-designed outcomes (e.g., jobs, monitoring access, habitat improvements) that address local priorities and inequities.

Co develop:
Joint design of project goals, methods, and monitoring with agencies, communities, and rights-holders.

Dual benefits:
Additional benefits (habitat, flood risk reduction, water quality, monitoring capacity) realized alongside the primary project goal.

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Dune:
Wind-built sand ridges along coasts; berms are engineered dune features for flood/erosion protection.

Ecosystem restoration (coastal):
Re-establishing or enhancing marshes, seagrasses, mangroves, ridges, and hydrology to improve resilience and services.

Environmental justice:
Fair treatment and meaningful involvement of all people, especially historically marginalized communities, in environmental decisions.

Executive order (EO):
Governor-issued directive that can set climate/resilience policy where legislation hasn't been passed.

Enhanced weathering:
Spreading and breakdown of finely ground minerals (often on land) to increase alkalinity delivered to waters and drive CO_2 uptake.

Flood Hazard Area Control Act (NJ): New Jersey regulations governing projects in flood-prone areas; often applies to basin retrofits and green infrastructure.

Free, prior, and informed consent (FPIC):
Rights-based standard requiring Indigenous consent before actions affecting their lands/waters/rights.

General permit:
A streamlined authorization for projects meeting standard criteria, avoiding full individual permit review.

Gigatonne (Gt):
One billion metric tonnes; used to describe global CDR scaling needs.

Green infrastructure (GI):
As used in the roadmap, refers to nature-based stormwater practices (bioretention, permeable pavement, swales, wetlands) that mimic natural hydrology.

Gray infrastructure:
Conventional engineered systems (pipes, pumps, tunnels, basins, bulkheads) for flood/stormwater management.

Hybrid:
Combined nature-based and structural elements (e.g., marsh sills with rock and planted marsh) for stability and habitat.

Hydrologic reconnection:
Restoring water flows (e.g., breaches, culvert upgrades, diversions) to revive wetland processes and sediment delivery.

Levee/sill (living shorelines):
Low-crested structures parallel to shore (sills) or higher flood barriers (levees) that attenuate waves and retain sediments.

Living shoreline:
Nature-based shoreline stabilization using plants, marsh benches, oyster reefs, coir logs, and light rock to reduce erosion while maintaining habitat.

Long-Term Control Plan (LTCP): NJDEP-approved plan for CSO communities outlining storage/treatment upgrades and timelines to reduce overflows.

Marine CDR (mCDR):
CDR approaches within rivers, coasts, or the ocean (see biotic and abiotic).

Meaningful engagement:
Engagement that is early, transparent, resourced, culturally relevant, and enables shared decision-making and co-design. (Definition adapted from Nawaz and Belotti, 2025.)

Monitoring, reporting, and verification (MRV):
The set of measurements, documentation, and third-party checks used to quantify and validate CO_2 removal and assess impacts.

National Environmental Policy Act (NEPA):
U.S. law requiring environmental review (environmental assessment / environmental impact statement) for major federal actions; often applies to restoration and large pilots.

National Pollutant Discharge Elimination System (NPDES):
Permit program for discharges to waters (MS4s, waste water treatment plants, industrial), implemented by SWRCB/regional boards in California and by NJDEP in New Jersey.

Nationwide Permit (NWP):
USACE programmatic permits for specific activities meeting impact limits (e.g., NWP 27 restoration; NWP 54 living shorelines).

Natural and working lands (NWL): Managed lands (forests, farms, rangelands, wetlands) that can store carbon and deliver climate benefits.

Appendix

Ocean alkalinity enhancement (OAE): Directly increasing seawater alkalinity (e.g., mineral or liquid alkalinity addition) to enhance CO_2 uptake and storage.

Open-system approach:
The use of diffuse environments to draw down carbon dioxide from the atmosphere. These stand in contrast to approaches that utilize contained systems where CDR can be measured in that same system. These approaches include CDR that happens in open fields, rivers, coasts and the ocean.

Outfall (coastal/wastewater): Discharge point to receiving waters (river, bay, ocean); often a candidate location for sampling or dosing systems.

Peatland:
Organic-rich wetlands that can be restored to reduce emissions and, in estuarine settings, generate/export alkalinity.

Permitting landscape:
The collective agencies, laws, and processes (federal, state, local) governing approvals for coastal and stormwater projects.

Ports:
Harbor facilities critical to state economies; part of economic weighting for enabling conditions. Can also be referred to as working waterfronts.

Practitioner-informed:
Refers to an approach, plan, or framework that is grounded in the real-world experience, insights, and day-to-day practices of individuals directly engaged in the field. In the case of this roadmap, the practitioners operate in the coastal resilience field.

Pump station (stormwater/CSO): Facility that moves large volumes of water; potential node for alkalinity dosing and monitoring.

Regional Water Quality Control Boards (California):
Nine boards under SWRCB implementing NPDES and water quality standards regionally.

Sediment diversion (Louisiana): Engineered openings in levees to deliver sediment- and/or nutrient-rich river freshwater to sinking estuarine wetlands for land building.

Sediment supply: Conditions of low/high availability of transportable sand/mud needed to maintain dunes and marshes.

Stormwater basin (detention/retention):
Engineered storage (surface or underground) to hold, slowly release, or infiltrate runoff; candidate for alkalinity dosing.

Stormwater management (coastal): Systems that handle rainfall/runoff and tidal backflow to reduce flooding, erosion, and pollution; includes green and gray infrastructure.

Thin-layer placement (TLP):
Spreading a thin layer of sediment over wetlands to raise elevation, maintain vegetation, and keep pace with sea level rise.

Tidal marsh/meadow:
Vegetated intertidal habitat providing wave attenuation, carbon storage, and alkalinity generation/export.