Tides Up
Nature-Based Solutions for Sea Level Rise
Nature-Based Solutions for Sea Level Rise

Emma Brentjens
Rachel Carson Council Stanback Fellow
Duke University

Sasha Provost
Rachel Carson Council Stanback Fellow
Duke University

Ana Young
Rachel Carson Council Stanback Fellow
Duke University

Bella Jaramillo, M.S.
Associate Director for Climate Justice
Rachel Carson Council

Robert K. Musil, Ph.D., M.P.H.
President & CEO
Rachel Carson Council
Table of Contents

Introduction ........................................................................................................................................ 1

Types of Coastal Protections ............................................................................................................. 4

Gray Infrastructure Solutions .............................................................................................................. 4

Green Infrastructure Solutions ............................................................................................................. 7

Socioeconomic and Environmental Justice Implications .................................................................. 12

Economic and Social Justice Impacts of Climate Change ................................................................. 12

Cost-Benefit Analysis of Green vs. Gray Infrastructure: A Gulf Coast Case Study ......................... 14

Inequitable Distribution of Shoreline Protection and Green Gentrification ..................................... 15

NBS and Indigenous Cultural Practices in New York and Hawaii .................................................... 16

Federal Investments in Climate Resilience ......................................................................................... 17

National Flood Insurance Program (NFIP) Shortcomings and Challenges ...................................... 18

Case Studies ...................................................................................................................................... 19

1. East Coast: Dare County ................................................................................................................ 19

2. East Coast: Miami-Dade County .................................................................................................... 22

3. West Coast: Salish Sea Region ....................................................................................................... 24

Recommendations ............................................................................................................................. 26

Endnotes ............................................................................................................................................ 27
INTRODUCTION

With its Coasts and Oceans Program, the Rachel Carson Council (RCC) draws attention to the environmental issues afflicting U.S. coastal communities and advocates for long-term sustainable solutions. Tides Up: Nature-Based Solutions for Sea Level Rise is a first-of-its-kind report from the RCC detailing the threats facing coastal communities, the long-term benefits of nature-based solutions (NBS), and the socioeconomic implications of these efforts. Tides Up grows out of the RCC’s mission to continue for contemporary times the legacy of marine biologist and renowned nature writer, Rachel Carson. Carson wrote the 1951 bestseller and U.S. National Book Award winner The Sea Around Us, as well as two other two books in her sea trilogy, The Edge of the Sea, and Under the Sea-Wind. Renowned for Silent Spring, her exposé of DDT and other pesticides that ignited the modern environmental movement, Rachel Carson was also an esteemed coastal conservationist. By exploring how to restore and enhance coastlines to their full potential, especially in a time of climate crisis, Tides Up carries on her vision.

This report brings together the research and efforts of various non-profit organizations, universities, and governmental institutions based in the United States regarding the efficacy of green and gray infrastructure for mitigating the effects of sea level rise (SLR) on coastlines. This report goes beyond a mere accounting of methods to put in context why NBS will be the driving force in a national movement to ensure a safe and sustainable future for all coastal communities.

Background

Over the past century, climate change has accelerated at an unprecedented rate. With warming temperatures, ice cap melt and water molecule expansion has caused sea levels to rise at a rate of 3.4 mm per year globally. Warming has also led to increased storm intensity. Warmer waters evaporate more readily while warmer air stores more water vapor, leading to more extreme rainfall and tropical storms. The combined threats of sea level rise (SLR) and increasing storm severity affect the 95,471 miles of coastline in the United States (U.S.) and the communities who call it home. With over 50% of the nation’s population living within 50 miles of coastline, adaptation is necessary to prevent disastrous flooding that could lead to massive property loss, displacement, deaths, and collapse of marine and coastal economies. Often, people of color and low-income communities bear the burden of these climate impacts, being more likely to live in high risk areas vulnerable to SLR and flooding.
To combat these risks, coastal towns and cities across the U.S. have implemented various shoreline protection measures that include both gray and green infrastructure. Gray infrastructure refers to hardened structures made of materials like concrete, metal, and stone, typical of the built environment. Green infrastructure, also referred to as nature-based solutions (NBS), encompasses approaches that use natural materials and living ecosystems to mimic natural environmental processes. While gray shoreline infrastructure like bulkheads and seawalls have dominated coastal protection efforts in the U.S., green infrastructure like living shorelines as well as restoration of natural habitat like wetlands, seagrass meadows, and coral reefs, are becoming increasingly popular, and with good reason.

While gray infrastructure solutions provide short term protection to coasts by blocking waves and storm surge, they only serve as a band-aid solution, requiring consistent costly repairs and exacerbating erosion over time rather than preventing it. NBS, like wetlands, seagrass beds, and coral reefs, absorb and reduce wave energy, rather than reflecting it like hardened structures. This allows them to accumulate sediment and develop resilience against coastal erosion. Living shorelines, a type of NBS that often uses marsh vegetation, but can include other natural materials, like oyster shells and coconut fibers, are often installed to restore these ecological functions in areas where they have degraded over time or been lost to development. While NBS often have a greater upfront cost than gray infrastructure, they provide more long term security and can support biodiversity and the economy within a region.

By preventing or reducing damage to property during severe storms, green infrastructure can save homeowners and municipal governments money in repairs. The protections afforded by NBS also support the marine and coastal economies, which contribute hundreds of billions of dollars in value to the country’s gross domestic product (GDP). Additionally, NBS strengthen the blue carbon...
Coastal ecosystems have a high capacity for carbon storage and sequestration, absorbing carbon dioxide ten times faster than forests. Companies, individuals, or other organizations can purchase carbon credits to offset their emissions, and this investment often funds conservation efforts. Carbon dioxide absorption by NBS also mitigates climate change, targeting the root cause of the environmental issues threatening coasts.

To maximize climate resilience, governmental and nonprofit organizations have launched ecosystem restoration and NBS implementation efforts across the country. The National Oceanic and Atmospheric Administration’s (NOAA) community-based restoration program has funded 205 living shoreline projects on the Atlantic, Pacific, and Gulf Coasts. NOAA has prioritized tribal efforts in their funding distribution, providing support for the restoration efforts of the Makah Tribe, the Quileute Tribe, and the Quinault Indian Nation along the Pacific Coast. Other government agencies, including the Department of Defense (DOD) and Department of Agriculture (USDA) have also been involved in coastal green infrastructure efforts. At the state and local level, research and nonprofit organizations like the Virginia Institute of Marine Science and Tampa Bay Estuary Program, working to restore seagrass meadows, the North Carolina Coastal Federation, planning to restore thousands of acres of wetlands, and the University of Washington, leading a three-year coastal resilience project, have made strides toward protecting and enhancing coastal ecosystem services.

While efforts to restore coastal functions have grown, gray infrastructure remains prevalent, covering 14% of U.S. coastlines as of 2015 and expanding to cover an estimated one-third of coastlines by the end of the century. In the wake of the recent $2.6 billion investment towards NOAA’s coastal resilience efforts through the Inflation Reduction Act (IRA), the RCC urges legislators and land managers to prioritize NBS to build community resilience to an ever-changing climate.
TYPES OF COASTAL PROTECTIONS

Coastal communities across the U.S. have implemented various shoreline protection methods in response to SLR, flooding, and erosion. Gray or hardened infrastructure like bulkheads and revetments are commonly installed along coastlines with varying levels of success and environmental impact, prompting some property owners and land managers to adopt nature-based methods. Natural shoreline protection methods, hereafter referred to as green infrastructure, exist in both nearshore and submerged environments. Examples of green infrastructure include wetlands, living shorelines, such as vegetation, oyster reefs, and structures made from natural materials (e.g., oyster shells, oyster castles, coconut fibers, etc.), and marine ecosystems like seagrass beds and coral reefs. Often these natural methods are used in combination with gray shoreline structures, like sills and breakwaters. The characteristics and benefits of the different shoreline protection methods are outlined in the following sections.

Gray Infrastructure Solutions

Stagnant Solutions: Bulkheads & Seawalls

Bulkheads serve two purposes: to limit shoreline erosion due to wave action and to protect coastal communities from storm surges. These impermeable structures are placed parallel to shore and aim to prevent the slide of land or sediment into the ocean. Rather than absorbing wave energy like living shorelines, bulkheads deflect it toward either end of the structure. While this initially maintains the shoreline, it interrupts the natural exchange of sediment. In some regions, this can result in sand moving in conjunction with incoming waves, causing erosion at the base of the bulkhead and accumulating on either end, leaving behind beaches that are rocky rather than sandy. This process can accelerate erosion on adjacent beaches lacking shoreline protection.

While bulkheads prioritize shoreline stabilization, seawalls are a popular gray infrastructure along coastlines predominantly built for the protection of coastal communities. While seawalls may also be curved or mounded, vertical structures are the most common. Similar to bulkheads, seawalls alter the natural exchange of sediment along the shore and accelerate erosion on adjacent beaches. Additionally, when built without...
consideration for shoreline ecosystems, their interruption of natural processes can result in damage to shoreline ecosystems. The negative impact of seawalls on local ecology and longshore drift can result in them doing more harm than good in the long-term despite short-term benefits to coastal communities.

Regardless of the negative environmental effects of seawalls and bulkheads, many have advocated for them as an essential protection measure of coastal communities. However, studies have shown that deflecting wave energy is less effective for long-term coastal protection when compared to structures that absorb or slow wave energy.

In North Carolina, Hurricane Irene damaged 76% of surveyed bulkheads, whereas marshlands and sills did not experience damage. Similarly, in New Jersey, bulkheads and seawalls have struggled to keep pace with rising sea levels, rendering them less effective than nature-based solutions.

When water washes over these structures, coastal communities flood, weakening the seawall and resulting in costly repairs. Additionally, since both seawalls and bulkheads shorten the beach width, incoming waves have less land slowing their movement towards shore, resulting in waves hitting the shore with more force. Considering the compounding negative ecological impact of these structures with their less effective coastal community protection measures, it is clear that bulkheads and seawalls are not the best solutions for long-term stabilization and protection.

Dynamic Solutions: Revetments, Breakwaters, & Sills

Dynamic solutions such as revetments, breakwaters, and sills may prove to be better adapted to the changing coastal conditions. Unlike bulkheads and seawalls, revetments seek to dampen, rather than deflect incoming wave energy. Since revetments are built as a sloping structure rather than a vertical obstacle, they permit water movement and diminish wave energy before deflection. This means that impermeable revetments, often built in conjunction with bulkheads and seawalls, can be more effective at stabilizing and protecting coasts than the aforementioned options. However, when placed too close to the water, these structures may also serve as a barrier to sediment movement and contribute to shoreline recession. To combat this issue, some communities have implemented permeable revetments. These structures, often made of stone or timber, also dampen incoming wave energy, but do so without interrupting water and sediment movement. This enables them to mitigate flooding without accelerating shoreline recession. Additionally, permeable revetments can be built with dynamic designs, enabling them to adapt to
the unique patterns of their shores. Cobble berms, a type of permeable revetment, are used along the Oregon coast. As the waves come in, the cobble is moved by the water, dissipating wave energy and becoming concentrated in higher intensity areas. This means that as conditions change, the cobble will continue to move to high intensity areas, mitigating the impact of incoming waves.

While permeable revetments are created as additives to best fit their location’s distinct conditions, breakwaters and sills embrace their location’s existing NBS and seek to enhance them. They present a synthesis of green and gray infrastructure, with breakwaters being well-suited for beach environments and sills to marshes. Unlike the aforementioned gray infrastructure solutions, which are placed along the coast, breakwaters are placed offshore. They are generally made of rock or concrete and operate similarly to barrier islands, which are islands that provide a barrier between the mainland and ocean. Their position enables them to absorb wave energy before it reaches the shore and promotes sediment accretion. This stabilizes coastal ecosystems and communities, creating calm conditions between the shore and breakwater. These new conditions can result in an increase in fish stock and the development of more robust intertidal ecosystems. Additionally, when made with the proper materials, breakwaters can serve as artificial reefs, increasing biodiversity within the area. While these effects are beneficial to coastal communities and economies, breakwaters can also contribute to downdrift erosion through disrupting the natural movement of water between the shore and structure. Therefore, for a breakwater to be successful, it must be developed to suit its specific environment in order to maximize the benefits without contributing to shoreline recession.

While breakwaters are well-suited to provide protection against wave energy for sandy and rocky coastlines, sills are designed to enhance and protect coastal marshes. Sills are built parallel to the shore and unlike other infrastructure options, they are low-lying structures. They are typically designed to blend with the surrounding ecosystem, coming only a few inches above the water level. These sills facilitate sediment accretion on a shoreline, provide additional stability to the area, and enhance the existing vegetation. After the sill is constructed, sand backfill and marsh vegetation are then added to the area. As waves crest over the sill, they bring nutrients and new organisms to the shoreline. The sill keeps the backfill and vegetation in place as it takes root, ensuring that wave energy does not disrupt the developing coastal marsh. These efforts replenish previously receded shorelines and help to create a thriving intertidal marsh ecosystem. During storms, these resilient marshes absorb and distribute incoming wave energy and water across dense vegetation and sediment. This slows and stores water that would otherwise contribute to flooding in coastal communities. When properly maintained, sills can remain resilient against stronger storms, providing long-term protection and benefits to coastal communities and ecosystems alike.
Green Infrastructure Solutions

Coastal Wetlands

Wetland types across the coastal U.S. vary widely, from salt and freshwater marshes to shrubby and wooded wetlands, like bottomland hardwood forests and mangrove forests. Over 15% of the coast is classified as wetlands, an area which constitutes about 40 million acres. Wetlands host an immense level of biodiversity, providing habitat for 40% of all species. Apart from their important role in ecosystems, wetlands also offer a variety of benefits and protections for coastal communities.

Wetlands have a high water-holding capacity, allowing them to store stormwater in saturated conditions. An extensive body of research suggests that coastal wetlands provide protections from floods during severe storms. One study modeling damage from storm surge and wave height and energy from Hurricane Sandy in New Jersey, New York, and Connecticut found that areas with denser and taller wetland cover had lower flood volume. Mangrove forests, a type of wetland consisting mainly of trees and shrubs typically found in subtropical and tropical brackish water estuaries, have also been found to reduce water levels during storm surge on the Gulf Coast of Florida during hurricanes in 2004 and 2005.

Marsh plants like cordgrasses increase friction against wave energy, reducing the rate at which water moves across the landscape. This absorption of wave energy reduces erosion and property damage. In 2015, research at the mouth of the Chesapeake Bay determined that a primarily cordgrass marsh reduced wave energy during two coastal storms. Even a relatively thin strip of marsh vegetation about 15 meters wide, like that which would be used for a living shoreline, can absorb as much as 80% of wave energy. The efficacy of wetlands for wave attenuation depends on various factors, including vegetation height and density, wave height, and the strength of the wave.

Wetlands also stabilize sediments thanks to the extensive root systems of marsh plants. Wave attenuation allows wetlands to accrete sediments because the slower movement of water allows suspended sediments to settle, further reducing erosion. A study from the Puget Sound region in Washington State found that marsh restoration at a site that was formerly drained and used for agriculture increased sediment accretion rates, even relative to natural marsh sites.

The mechanism by which wetlands accumulate and retain sediments and absorb wave energy also allows them to improve water quality, filtering out suspended solids and other pollutants. For example, wetlands reduce nutrient runoff from agricultural fertilizers, which can have detrimental effects on aquatic ecosystems and coastal communities by causing toxic algal blooms and fish kills.
According to a study simulating wetland restoration, a 10% increase in wetland extent in areas most impacted by nitrogen pollution can reduce nitrogen loading by more than 50%. Additionally, a report from Point Blue, a conservation science nonprofit organization, explains that coastal wetlands can also remove waterborne pathogens, further improving water quality.

In addition to providing flood and wave attenuation, mangroves act as strong wind buffers, reducing wave formation. Additionally, previous research has shown that mangroves can be more effective for erosion control than salt marshes because of their thick root systems. While mangroves are more vulnerable to storm damage than marsh plants, they have been found to recover quickly after hurricanes, in some cases regrowing significantly after a few months.

To capture the numerous benefits provided by marshes, restoration projects are prevalent across the coast. The North Carolina Coastal Federation, a nonprofit organization focused on coastal protection and restoration, seeks to restore 8,000 acres of wetlands in collaboration with the Department of Agriculture’s (DOA) Natural Resources Conservation Service. The initiative has already restored wetlands in three counties. The Water Resources Division of the National Park Service (NPS) is also involved in wetland restoration efforts in the Florida Everglades, Cape Cod, Santa Cruz Island, and other coastal parks. The Everglades restoration, which aims to provide ecosystem protection, flood mitigation, and water, is the largest hydrologic restoration project in U.S. history, with a $10.5 billion investment.

Seagrass meadows, another type of coastal wetland, grow in shallow salt and brackish waters across the earth. Unlike many seaweeds and algae, seagrasses have roots and can form thick patches underwater. Seagrass meadows are the foundation of many marine and estuarine ecosystems, providing habitat for a wide variety of marine animals including vulnerable and endangered species like manatees and green sea turtles.

Like other wetlands, seagrass meadows stabilize and accumulate sediment and reduce wave energy. Both tall and short seagrasses can accumulate sediment by slowing the movement of water and allowing sediments to settle, including fine particles. Larger seagrass beds are more effective at accreting sediments as the movement of water around smaller, sparser beds can actually increase turbulence and cause more erosion. Therefore, it is important to conserve large areas of seagrass to maximize their coastal protection benefits.

Seagrasses are sensitive to increases in temperature, low dissolved oxygen levels, changes in salinity, algal blooms, and other environmental factors. Changing conditions due to climate change and human activity have caused a steep decline in the habitat of about 7% each year as of 2009. For this reason, efforts to restore seagrasses have taken root across the U.S. In some instances, seagrass restoration is undertaken as a requirement under the Clean Water Act, as is common in Florida, where coastal development has resulted in seagrass loss.

The most common restoration methods are planting seagrass seeds or transplanting shoots with varying success. In the Chesapeake Bay, the Virginia Institute of Marine Science began planting seagrass in 1999 across hundreds of acres which has since expanded to over 6,000 acres by 2015. Similarly, the Tampa Bay Estuary Program has restored more than 40,000 acres of seagrasses between
However, restoration efforts have often been fraught with challenges. Seagrass restoration projects across the world have yielded a survival rate of less than 40%, partially due to their sensitivity to various environmental conditions. Even the successful Tampa Bay project took decades and required cooperation from local governments and corporations to reduce nitrogen pollution and foster conditions that support seagrass recovery.

While numerous studies have found positive effects of seagrasses on shoreline protection, there remain significant knowledge gaps due to a lack of research and mixed findings from existing studies. The need for additional research is urgent as seagrass meadows decline globally.

Wetlands also play an important role in climate change mitigation as major carbon sinks, sequestering and holding a disproportionately large amount of carbon. Wetlands cover about 5-8% of earth’s surface, but hold 20-30% of all soil carbon. Seagrass meadows specifically hold about 5% of global carbon dioxide.

Additionally, evidence shows that coastal wetlands sequester 10 times more carbon each year than mature tropical forests.

A special report from the Intergovernmental Panel on Climate Change (IPCC) found that reducing warming to 1.5°C and reaching net zero emissions by 2050 will necessitate removing carbon dioxide from the atmosphere, and wetland conservation will be critical to that effort. Mitigating the root causes of climate change and associated increase in storm severity through greenhouse gas sequestration is crucial to the health and longevity of coastal communities into the future.

**Oyster reefs**

Oyster reefs are clumps of shell-protected oysters forming colonies. The reefs are natural breakwaters, protecting shorelines from waves and erosion, as well as providing a slew of ecosystem services, including a form of blue carbon storage, which refers to carbon sequestration by marine ecosystems.

The reefs may be natural, artificial, or a mix. Contemporary artificial reefs are bound by netting or in oyster castles, which are interlocking concrete and oyster shells, and often reuse old oyster shells as habitat for oyster larvae as they grow into juveniles.

Due to their adaptability, oyster reefs are a powerful resource against SLR. The intertidal reefs can provide wave height and energy attenuation reduction between 30-50% and also grow vertically in tandem with the rate of the rising seas, given a relatively low erosion strain. One study found that the reefs may “match even the highest predictions of SLR by the year 2100.” Additionally, the reefs can assist as a measure against climate change. A study of 19 oyster reefs within proximity of the Rachel Carson Natural Estuarine Research Reserve in North Carolina found that these reefs can capture carbon at similar rates to other blue carbon sinks globally, such as mangroves, seagrass, and salt marshes.
Other ecosystem services that oyster reefs provide include serving as marine habitats and nurseries for hundreds of species of fish, shellfish, among other invertebrates. Additionally, a single oyster can filter through up to 50 gallons of water a day to seek out the nutrients they need for survival.\(^8\) A single square yard of oyster reefs may consist of 5,895 oysters, meaning that large oyster reefs filter enough water to combat eutrophication, also keeping seagrass ecosystems healthy to help prevent shoreline erosion.\(^8\)

Oyster reefs form in coastal salt waters and are most commonly found in North America throughout the East Coast and in the Salish Sea and San Francisco Bay regions. Recent popularity in the efficacy of this practice has led to newly commissioned artificial oyster reefs for coastal erosion protection in shallow waters.\(^8\) This practice has a long history in North America; oyster reefs have been used for over 6,000 years by Indigenous peoples on the continent before the arrival of European colonizers in the late 1400s.\(^8\)

Despite its promise as an NBS to erosion and protecting coastlines, oyster reef efficacy faces a threat from oyster harvesting. There has been an 85% decrease in oyster reef prevalence globally to the current day.\(^8\) Additionally, SLR remains an existential threat toward these reefs, as intertidal oysters grow 34% faster and more voluminous than their subtidal counterparts,\(^8\) which are much less effective against wave attenuation and energy and erosion. Even with vertical growth, if oyster reefs become subtidal, they lose their efficacy as a living shoreline.

To combat the harvesting and climate related threats that oyster reefs face, further investment in oyster reefs is a plausible solution, as higher levels of water filtration provided by a greater density of oysters will lead to suitable conditions for the oyster reefs to adapt to rising sea levels. Additionally, implementing oyster harvesting restriction policy as well as stricter and narrower permitting laws would mean protection in the oyster reef investments and higher levels of efficacy for this NBS.

**Coral reefs**

The United States is home to 3100 km of coral reef systems stretching across the Southern coasts, Hawaii, and other island territories that fall under U.S. jurisdiction.\(^8\) These reef systems, while integral to marine biodiversity and the coastal tourism industry, also play a large role in the protection of citizens and property from the effects of storm surge and flooding. In terms of hazard risk mitigation, U.S. coral reef systems are valued at $1.8 billion annually due to their ability to dissipate up to 97% of incident wave energy.\(^8\) The tempering effect of reef systems on wave energy also reduces the size of potential flood plains in coastal communities.\(^8\) This results in less damage from coastal flooding and protects thousands of people and their livelihoods from disruption and displacement.

This is seen in a decade-long study in Hawaii that found that communities adjacent to protected reefs experienced half the flood losses as those with degraded reefs. On Maui alone, three reef systems provided risk reduction benefits of an estimated $5 million annually, demonstrating the economic value of protected coral reefs.\(^8\) Similar studies in South Florida and the U.S. Virgin Islands have correlated similar benefits from reef conservation.\(^8\) However, a combination of damage
from coastal development, destructive human activities, and ocean acidification and pollution has severely degraded coral reefs. This has resulted in coral reefs vertically eroding, leaving a larger gap between the crests of coral reef systems and sea level.\textsuperscript{91} This limits the ability of coral reef systems to reduce wave energy and storm surges. A one meter loss of coral reefs would increase annual flood risk in the U.S. by a projected 77%, with a greater risk for island territories.\textsuperscript{92} Projections anticipate an increase of 263\% in Puerto Rico, 127\% in American Samoa, and 120\% in the U.S. Virgin Islands.\textsuperscript{93} This leads many to advocate for the protection of coral reefs as a method of long-term risk mitigation in the coastal U.S.

Beyond nature-based conservation policies, there have also been efforts to combine artificial structures with existing coral reef systems, with the goal of accelerating reef accretion. X-REEFS, a DOD-funded project, received a $7.5 million grant in 2022 to develop hybrid biological and engineered structures.\textsuperscript{94} In the Florida Keys, efforts to create artificial reefs and restore existing reefs through underwater coral farming and coral colony transplants have also been successful in revitalizing damaged reef sites.\textsuperscript{95} These initiatives demonstrate the potential for a combination of green and gray infrastructure as an effective path forward in restoring U.S. coral reef systems.

Coral reef monitoring is important to implementing conservation and restoration efforts. In 2021, NOAA also began implementing their Coral Reef Conservation Program (CPCP).\textsuperscript{96} This program includes a comprehensive and standardized long-term valuation of U.S. coral reef systems, helping to identify areas that will benefit the most financially from coral reef conservation. Additionally, it will demonstrate which conservation methods have been most successful across different coastal regions.\textsuperscript{97} CPCP will inform future conservation policy and impact which strategies are prioritized to support more effective conservation and coral accretion in the coming decades.
Economic and Social Justice Impacts of Climate Change

The two types of economies most impacted by SLR in the U.S. are coastal economies and marine economies. According to resources from the National Ocean Economics Program, coastal economies, which include any metropolitan area, county, or town located in close proximity to the ocean or Great Lakes region, provided over $9 trillion in wages and over $23 trillion to the U.S. GDP in 2021.98 Marine economies include the industries, economic activities, assets, goods, and services related to marine ecosystems, on both oceanic coasts and in the Great Lakes region.99 The marine economy is divided into the following sectors: living resources, marine construction, marine transportation, offshore mineral extraction, ship and boat building, and tourism and recreation.100 A recent report from the U.S. Bureau of Economic Analysis revealed that the marine economy accounted for 1.9% of the nation's GDP in 2021, translating to $432.4 billion, a 7.4% inflation-adjusted increase from 2020. NOAA's latest report from 2020 found the marine economy consists of 164,000 business organizations and 2.9 million employees.101 Considering the millions of jobs and multitrillion-dollar GDP provided by these economies, SLR presents an impending economic crisis if coastal regions do not invest in climate change adaptation and resilience.

Under current emission trends, the global temperature, which is currently 1.1% hotter than pre-industrial times, is on track for a 2% increase by 2050, considered by experts to be a threshold for severe climate-related events.102 A 2016 report that estimated equity exposure based on potential temperature simulations found that in the U.S., labor intensive industries, like hospitality, fishing, construction, and healthcare, and including those within the marine and coastal economies, face major potential economic losses as temperatures increase and storms become more severe.103 The inelastic rates of demand from climate change will cause major risks in terms of future growth and opportunity loss.104
Without infrastructure reforms, the projected annual structural losses increase to nearly $1 trillion by 2050.\textsuperscript{105} The East and Gulf Coasts are the most vulnerable areas in the contiguous U.S. to SLR due to the high population density, flat landscape, and frequent hurricanes, which are the most costly climate disasters.\textsuperscript{106} The West Coast also faces severe SLR risks, with a projected SLR of seven feet before 2100 in the Bay Area, California.\textsuperscript{107}

Population density on the coasts is over five times greater than the national average. Shoreline communities contain over 128 million people despite comprising just under 10\% of the nation’s land area.\textsuperscript{108} From 1970 to 2010, these coastal shoreline communities welcomed an average of 125 new occupants per square mile; a growth that is anticipated to continue at a steady rate in the coming decades.\textsuperscript{109}

These communities additionally encompass a diverse range of identities and socioeconomic statuses. Notably 64\% of the nation’s Asian population, 60\% of the Native Hawaiian and Pacific Islander population, 47\% of the Black population, and 49\% of the Hispanic or Latino population live in coastal communities.\textsuperscript{110} When considering that the same region is home to just 35\% of the white population, it’s evident the effects of SLR will disproportionately impact marginalized communities.\textsuperscript{111}

A 2021 EPA report found that with 50 cm of global SLR, American Indian and Alaskan Native populations are 48\% more likely and Black populations are 11\% more likely to live in places with the highest expected percentage of inundated land.\textsuperscript{112} With 100 cm of global SLR, the primary impact shifts to Hispanic and Latino populations, who are 47\% more likely to live in high-impact areas. Additionally, the report projected that the Southeast-Atlantic and Southwest regions would have the largest populations living within high-impact areas. In both of these regions, over half of the population consists of minorities.\textsuperscript{113}

The inequitable effects of SLR are also seen across income levels. With 50 cm global SLR across all regions, low-income communities are more likely to be situated in high-impact areas due to the higher flood risk equating to a lower cost of living. This can create a distinct challenge for those paid on an hourly basis, with infrastructure damage and businesses closing due to flooding. This may result in lower weekly incomes and a lack of job security. With 100 cm of global SLR, coastal traffic delays are expected to increase by an annual average of 63 hours per person. These projected delays are increased in the Southern Great Plains and Southeast-Gulf regions where the anticipated annual average per person is expected to reach 205 and 189 hours, respectively.\textsuperscript{114} Similar to risk from SLR, this impact is not spread evenly across minority groups. Pacific Islander, Asian, and Hispanic or Latino populations’ delay impact is projected to be higher than other demographics. Additionally, without reliable infrastructure, impacted populations experience reduced proximity to economic opportunities in adjacent communities.\textsuperscript{115} This issue also contributes to limited access to essential infrastructure such as medical facilities, schools, and public transportation, furthering the negative effects on coastal communities.
Cost-Benefit Analysis of Green vs. Gray Infrastructure: A Gulf Coast Case Study

To mitigate the impact of SLR on coastal communities, local and federal governments should prioritize cost-effective infrastructure solutions. In many cases, the most efficient mitigation approaches for SLR adaptation are a mix of mostly green infrastructure solutions with complementary gray infrastructure, as well as policy changes, like zoning laws restricting shoreline development. Solely implementing gray solutions are cost-intensive and ineffective in the long term due to their lack of adaptability and need for more frequent repairs. NBS, however, are able to adapt to SLR as living, dynamic ecosystems.

These NBS solutions would not only safeguard coastal communities, but also provide greater returns on investments (ROI) than gray solutions, referring to the amount of money earned relative to the amount invested. This is partly due to the financially valuable ecosystem services NBS provide. Seagrass beds, for example, generated $253 billion in fishery sales in 2020 by providing critical habitat for fish populations. However, despite the effectiveness of NBS, the quickest mean time for an ROI was 18 years in mangrove restoration, meaning that these investments are necessary as soon as possible.

NBS also provide significant value in damage prevention from their protective services. A 2018 study from a group of climate resilience researchers conducted a cost-benefit analysis (CBA) of infrastructure adaptation solutions for SLR on the Gulf Coast. The total risk costs and damage prevention benefits were calculated based on annual expected damages in the Gulf Coast region throughout a 20-year period, while probable risks were calculated using a simulation from the historical distribution and severity of storms in the region, considering changes in intensity and frequency due to climate change. The study specifically examined how NBS and gray infrastructure solutions perform with regards to wave attenuation, flood protection, and structural disturbances, as well as the projected costs and lifetime of each measure. The study found that sandbags were the most cost-effective measure, setting the highest benefit-to-cost (BTC) ratio of 10.0, meaning that the benefit of sandbags in terms of damage reduction most greatly outweighed the cost of their implementation. However, sandbags were not effective in the long term, and were noted only to be a temporary solution. The next most cost-effective solution the study found for SLR adaptation were all NBS, with marsh and oyster reef restoration together providing the most damage reduction, or benefit, compared to their cost of implementation than any other combination of solutions. While gray and policy solutions provided the highest total value in damage prevention at $58.6 billion over the 20-year period for local levees and home elevation, the CBA revealed that these measures have a low cost efficiency, with just 0.99 and 0.73 BTC ratios, respectively.

The policy and infrastructure solutions explored in the study could provide a combined $57.4 billion in damage reduction from SLR and climate-related storms, with 85%, or $49 billion, contributed by NBS. These results suggest that the most effective adaptation would be a mix of green and gray, with mostly investments into green solutions.
Existing measures have the potential to protect up to 80% of property. Yet, the map shows wide gaps in protection throughout the coast, especially in the areas of highest levels of social vulnerability.

A report by Oxfam America, an organization working to end poverty and inequality, found that the Gulf Coast region is also home to some of the nation's highest social vulnerability, particularly in the coastal plains. According to the social vulnerability index, as calculated by the poverty rate, elderly population, the level of climate risk, and climate resilience, Louisiana and Mississippi are the two states most at-risk. Additionally, Louisiana's coastline areas that are not protected by any measure besides island barrier restoration, such as St. Mary Parish, Iberia Parish, and Vermillion Parish, have respective populations of Black residents of 31.4%, 31.2%, and 14.1%. Similarly, Mississippi has just three coastal counties, but the only risk prevention the area has is ecological restoration of barrier islands. Mississippi's coastal counties, Hancock, Harrison, and Jackson, are respectively 85.2%, 64.9%, and 68.7% Black. The data demonstrates that the benefits of shoreline protection are not reaching the most vulnerable communities.

**Inequitable Distribution of Shoreline Protection and Green Gentrification**

Unequal application of shoreline stabilization practices across U.S. coasts, which serve to prioritize the protection of property over support for existing coastal populations, has led to inland retreat of low-income communities. While the aforementioned green and gray infrastructures have been used to stabilize shorelines, the U.S. government has also sought to mitigate risk through property buyouts. This is a practice in which a government agency purchases private property from residents and communities, removes all existing structures, and then maintains the empty land as a natural floodplain. Those who have sold their land use their funds to relocate farther inland, typically to an area with lower flood risk. While retreat can be a beneficial solution for areas that experience repeated damage from SLR and flooding, this process is often informed by systemic injustice. A study in North Carolina found that property buyout programs were correlated with the target area having high racial diversity and lower home values and household incomes. Conversely, the same study found that the implementation of shoreline stabilization efforts were more common in areas with lower levels of racial diversity and higher home values and household incomes.

The relationship between program implementation and socioeconomic status reveals a system that serves to protect the properties and industries in high-income coastal communities through encouraging the retreat of low-income coastal communities.

Furthermore, even as shoreline stabilization practices are applied to coastal communities and cities, they are often implemented without a framework to prevent an increase in rent or cost-of-living in the region. This issue, referred to as green gentrification, also fuels the displacement of low-income communities. For those in coastal cities, this often results in a move away from neighborhoods with access to water amenities, economic opportunities, and higher property values to neighborhoods.
with less protective infrastructure and a greater flood risk. A study from Miami reflects this, finding that people with lower incomes were largely constrained to neighborhoods without water amenities and with a high inland flood risk. Additionally, neighborhoods with higher Mexican populations were found to experience inequitable exposure to coastal flooding. Studies focusing on the impact of Hurricane Harvey in Houston similarly found that the impact of flooding significantly increased in predominantly Black and Hispanic neighborhoods and that low-income residents are more likely to live on low-lying land. The same was observed in New Orleans studies in which a lack of open space and outdated infrastructure in Black neighborhoods was associated with increased flood severity.

When shoreline stabilization programs are implemented without comprehensive consideration, they can force the migration of pre-existing communities and leave marginalized populations vulnerable. This fuels the inequitable distribution of flood risk across identity and income level and facilitates processes that make coastal living inaccessible and unsafe for communities lacking the resources to protect themselves against the unprecedented threats that SLR and high-tide flooding present. Therefore, land managers must consider the social justice implications of green infrastructure development to ensure marginalized communities are not left behind.

**NBS and Indigenous Cultural Practices in New York and Hawaii**

Understanding the cultural significance of NBS is also critical to ensuring just and equitable solutions for coastal resilience in Indigenous communities. Coastal ecosystems have long been intertwined with cultural practices of Indigenous communities, including American Indians and Alaskan Natives, such as retrieving plants for medicinal purposes or food items for traditional dishes. The sites where Indigenous populations live are also often considered sacred to their Tribe and losing the ecosystem services could lead to major disruptions in long-standing traditions.
The Shinnecock Nation is an Indigenous tribe in eastern Long Island, New York. The Shinnecock, which in Algonquin translates to “people of the stony shore,” rely on the shoreline and wetlands for cultural resources like seashells used to make beads and traditional foods, including finfish and shellfish. Additionally, SLR threatens the tribe’s ancestral burial grounds. To protect their natural resources and sacred sites, the community has begun a habitat restoration project involving planting cordgrasses, recovering oyster reefs, and installing a line of boulders around the shore as additional wave protection. This practice of ecological restoration is nothing new, as mentioned earlier with the use of oyster reefs for thousands of years by Indigenous peoples in North America.

Habitat restoration may also indirectly maintain cultural resources beyond its intended purpose. For instance, coral reefs are one of the most cost-effective solutions for SLR, and are most abundant in Hawaii, Puerto Rico, and the other U.S. territories. Hawaii and the Pacific U.S. territories, including Guam and American Samoa, have Indigenous populations that are not federally recognized and therefore do not receive the same coastal resilience funding as the 567 federally recognized American Indian and Alaskan Native tribes. However, Native Hawaiians specifically have a special spiritual relationship with coral reefs, and believe these ecosystems are the oldest of all other organisms in Hawaii and should be safeguarded.

To assist the local culture, fishing industries, and ecosystem services, NOAA is funding community-based coral reef restoration in Hawaii to support subsistence and recreational fishing. This measure will also ensure more Indigenous communities are protected against SLR, as coral reefs prove risk protection for the entirety of the U.S. beyond $1.8 billion annually. The top one meter of coral reefs also reduce the nation’s 100-year flood zone by 23%, preventing $2.7 billion in flood damage to properties.

Federal Investments in Climate Resilience

The U.S. has already begun investing into NBS through legislation most directly allocated toward NOAA. For instance, the Infrastructure Investment and Jobs Act, known commonly as the Bipartisan Infrastructure Law (BIL), provides nearly $3 billion throughout five years for investments in resilient blue infrastructure, with $207 million allocated to habitat restoration projects through the National Coastal Zone Management Program, $77 million for restoration projects in the National Estuarine Reserve System, and $492 million going toward the National Coastal Resilience Fund grants.

Similarly, the Inflation Reduction Act (IRA) of 2022 provides a complementary $2.6 billion toward NOAA in funding for proactive measures for climate-related severe weather events and community protection, including climate resilience grants, Tribal support, projects in climate adaptation for fisheries, a business accelerator program that supports coastal and marine economies, and helping fund jobs that support climate resilience.

The Biden-Harris administration has promised further funding through FEMA, with more than $3 billion from the Building Resilient Infrastructure and Communities (BRIC) annual grant program. FEMA also received an additional $160 million in funding, including more than $50 million for Tribal nations. This historic investment in building community resilience is directed at closing a gap in environmental justice communities where the projected effects of global SLR and high-tide flooding are likely to be exacerbated by an outdated and expensive insurance system. With the level of monetary and livelihood protection benefits that NBS can provide, bills in Congress with consideration of further NBS investments should be prioritized.
National Flood Insurance Program (NFIP) Shortcomings and Challenges

FEMA estimates that an inch of flooding within the home has the potential to cause over $10,000 in total damages. As either the depth of the water or the size of the home increases, the minimum estimated combined loss potential increases. This damage can be devastating to coastal households, especially in low-income communities, leading to a multitude of challenges when trying to rebuild after storms or high-tide flooding. The financial strain of this damage is magnified for those without flood insurance, a demographic that includes the majority of Americans in coastal regions and inland zones. The publicly-funded National Flood Insurance Program (NFIP) is the sole option for the majority of coastal homeowners.

NFIP determines premium pricing on an individual basis, with the annual cost reflecting anticipated risk, meaning that the annual cost of insuring a home in a high-risk area can range from hundreds to thousands of dollars, which many low-income households cannot afford. Furthermore, NFIP policies only cover the home and belongings within the home. This means that there is no support for the cost of temporary housing if a household is displaced. This can present an additional financial burden for impacted households and make it difficult for occupants to continue traveling to their routine workplaces, schools, and healthcare providers in the aftermath of flood damage.

NFIP’s limited coverage and expensive annual cost are due to both a severe lack of funding when compared to the program’s demand and to encourage homeowners to move farther inland, therefore limiting the cost of aid needed after natural disasters and flooding. As the floodplain and severity of damage continues to increase in the coming decades, it is likely that the annual cost of NFIP will continue to rise, creating a system that does not make flood insurance affordable to the marginalized individuals who are projected to be disproportionately affected by SLR and flooding.

The inequitable access to flood insurance is just one of many factors serving to widen the wealth disparity in coastal communities. Without the ability to afford flood insurance, many low-income individuals are forced to move farther inland, often resulting in a greater distance between individuals and their occupation and a loss of community ties. Comparatively, individuals who can afford flood insurance for their primary or seasonal homes, often those with greater disposable income, are able to avoid displacement from their communities.

Investments in coastal protection initiatives should consider both potential ecological and financial benefits and impacts on local communities, whether it be unequal protection or green gentrification that shifts the burden from environmental to economic. Inequities in coastal stabilization and protection are present in every aspect of the field, from program distribution to federal insurance accessibility. As investment in shoreline stabilization increases, it is essential to focus on the protection of marginalized communities who bear the greatest climate impacts and to ensure that implemented solutions do not displace low-income communities. By including environmental justice research in future policies and programs, legislators can ensure that support is reaching those who need it most and increase the resilience of coastal communities across the U.S.
CASE STUDIES

As the seas continue to rise, cities, towns, communities, and the lives that their inhabitants once knew will all suffer major losses. Rising seas lead to erosion and storm surge that not only causes diminishing beaches, but for some places, it also leads to flooded or damaged properties, which means the loss of sacred land and valuable land tracts. A study conducted by Climate Central found through over 250 individual county-level reports on acreage and parcels affected by rising seas that before the mid-century point, the Earth's maps will need to be redrawn. Just in the U.S., over 648,000 individual tax parcels, equivalent to 4.4 million acres of land, are expected to be either entirely or partially underwater. By the turn of the century, the value of property at risk in the U.S. will be at least $108 billion. The states that face the greatest loss of parcels at more than 40,000 parcels each are Florida, Louisiana, Texas, North Carolina, Virginia, and New Jersey, respectively. This potential loss of property, and therefore property taxes, marks a steep decline in essential funds and tax revenue that the U.S. needs to pay for emergency services and education. With much of the coastal U.S. already experiencing the impacts of SLR, communities have begun investing and implementing shoreline protection measures. This section examines three at-risk areas, two of which are expected to either completely flood over, leaving them inhabitable, or lose more than 50% of their properties by 2100 under a projected 5.28 foot sea-level increase data mapping. Additionally, the section discusses the adaptation strategies already in place in these locations, as well as possible investments specific to the landscapes.

1. East Coast: Dare County

The Outer Banks (OBX) are a chain of 200 mile-long barrier islands off the coast of Virginia and North Carolina defined by constant modification of their rugged landscape and sedimentary deposits by waves and currents. The islands, which comprise the eastern-most parts of North Carolina, border the Atlantic Ocean on their right and the Albemarle-Pamlico Estuary on their left. The OBX features both major inlets, which are the Oregon Inlet, the Hatteras Inlet, and the Ocracoke Inlet, and dynamic inlets, meaning the number of inlets may change according to sea level, and that even the sound side of the islands and their wetland ecosystems may flood due to rising tides. One of the nation's most popular tourist destinations, National Park Service sites received nearly 4 million tourists in 2021, with about 3.2 million visiting the Cape Hatteras National Seashore. Additionally, Dare County, which contains most of the OBX, has one of the state's largest tourism sectors, with the fourth largest spending income at $1.826 billion in 2021.

Dare County is one of the most at-risk areas of SLR induced-flooding in the nation, with about 77% of homes facing severe risk, 87% of roads facing moderate risk, and 79% of commercial properties facing extreme risk, the highest risk level that would mean destroyed infrastructure and properties, throughout the next 30 years. Additionally, almost 83% of critical infrastructure facilities, including hospitals, fire stations, and police stations, face major risk of flooding. Risks to North Carolina's barrier islands also threaten mainland communities. Map projections show that as little as two feet of SLR will cause some counties bordering the Albemarle-Pamlico Sound, like Tyrell, Hyde, part of Dare, and Currituck, to turn into islands of much smaller land mass than their current sizes. Under this SLR projection, which is expected to happen before 2060, the OBX will lose much, if not most of its wetlands, and traveling between them may become nearly impossible due to the loss of highway. The expected 5.28-foot rise by 2100 would leave Dare County almost entirely covered by water and the
county’s year-round population forced to rebuild their lives elsewhere. On mainland Dare County, the Albemarle Pamlico Peninsula is at risk of losing 750,000 acres to SLR, an area which includes the Alligator River National Wildlife Refuge, a 154,000-acre protected area.

Most houses in the OBX are built upon stilts at least eight-feet high, but this has proved to only be a short-term structural solution for flooding. In 2022, the effects of SLR in the OBX began making national-headlines as three shoreline homes in Rodanthe, a small town in Dare County and the easternmost point of North Carolina, collapsed into the ocean from the culmination of erosion caused by hurricane damage, nor’easters, and rising tides. A fourth home collapsed into the ocean in March 2023, and more than a dozen remain at risk in the town, causing many homeowners to either abandon their houses to the sea and pay the cost of cleanup or pay hundreds of thousands of dollars to move the home to the back of their land parcel or even purchase new parcels farther away from the sea. Homeowners are responsible for the cost of moving homes away from the ocean. However, if the home is lost to the sea, the Federal Emergency Management Agency’s (FEMA) National Flood Insurance Program, a multi-thousand dollar policy that is required for homeowners in flood zones such as the OBX, will provide owners up to $250,000 for the property loss and $100,000 for the items inside.

The flat-lying OBX have seen inconsistent seashore loss throughout the past few centuries, but in the current century and the last century, the waters have had increasingly higher rates of erosion and SLR. For instance, the 200-foot Cape Hatteras Lighthouse, a landmark of the islands, was 1,500 feet from the shore when it was built in 1870, but it was only 120 feet from the ocean by 2000, forcing the NPS to move the
lighthouse 3,000 feet inland to save it for the time-being. Additionally, the current erosion rates of 13 feet annually lost in the OBX have caused more than 200 feet of shoreline loss in some areas in the past 20 years. As flooding and property collapsing persists, many OBX communities have turned to adaptation measures.

Erosion is a natural process for barrier islands, but the immense amount of oceanfront coastal development means that homes are now at risk of eroding away with the sand. As a resolution to the threats that development faces from nature, the county has been left with slim choices to mitigate the erosion. The towns of Avon, Buxton, Duck, Southern Shores, Kitty Hawk, Kill Devil Hills, and Nags Head have each invested in beach nourishment. Planning for these programs takes about 10 years, and they require consistent upkeep. Maintaining beach nourishment projects means that the sands need to be re-pumped to elongate the shores every five years as erosion continues to eat away at the coast. Additionally, this process is very expensive, costing between almost $6.4 million to about $18.1 million in most towns of Dare County. However the town of Rodanthe cannot afford beach nourishment measures. A report from Coastal Science and Engineering finds that unlike the cost of other towns in Dare County, for Rodanthe, dredging would have a price tag of $40 million, a levy that would add up to $175 million throughout 30 years. This is infeasible given the town’s small tax base and the long line of other public lands in need of federal funding in front of it. For now, the county’s solution for Rodanthe is the Jug Handle Bridge, a 2.4 mile bridge in the shape of a jug handle that goes around the Pea Island National Wildlife Refuge. The bridge, which opened in 2022 and cost $145.33 million, will not save Rodanthe from sinking, but provides a several-decade long solution to the loss of stretches of highway the town is expected to lose.

On the back barrier, Dare County has more options for coastal protection thanks to the prevalence of marshes and wetlands. In the past, a mix of gray and green infrastructure has been used on the back barrier as protection, including bulkheads, riprap revetments, sills, marshes, and beaches. In a study published by Ocean & Coastal Management that analyzed the damage of protection measures along nearly 47 miles of sound side shoreline of the OBX, 76% of bulkheads, the main shoreline protection method, in Rodanthe, Waves, and Salvo were damaged after Hurricane Irene. The same study found no recorded damage to marshes or mash sills, implying that shoreline hardening was less effective both physically and financially.

Recognizing the strength of investing in green infrastructure over paying for shoreline hardening, organizations including the North Carolina Coastal Federation are assembling teams and endowing new and existing living shorelines, including oyster castles and salt marshes, along the Outer Banks and coastal North Carolina. Another organized project focused on enhancing salt marshes is the South Atlantic Salt Marsh Initiative, which formalized a plan to implement recommendations for salt marsh conservation that its governmental, community, stakeholder, and scientist partners will follow over the next five years for their resilient coastline agendas. The plan will work to upgrade the wetlands throughout the four South Atlantic states — North Carolina, South Carolina, Georgia, and Florida — so that they are better equipped for SLR. Grants of over $1.25 million funded the
creation of 1,900 feet of oyster reefs, seven acres of oyster sanctuaries, hydrologic restoration that protected 11 miles of shore, invasive Phragmites control for 11.5 acres of marsh, and the planting of 20,000 coastal resilient trees among other implementations. Additional actions for the project include implementing more living shorelines as well as upgrading the marshes.

With 12,000 miles of estuarine shoreline in North Carolina, the state and Dare County have options to keep the back barrier coastlines and the peninsula-side Alligator River NWR and Dare Game Land safe from SLR. Hardened structures and other gray solutions have been found to quicken erosion and serve as temporary fixes, but oyster programs in estuaries have proven effective for wave attenuation, so much that the state’s commercial oyster industry led an oyster shell recycling project through the Coastal Federation called Restaurant to Reef. Additionally, enhanced tidal marshes can liven ecosystems and provide ecosystem services such as blue carbon and increasing fish availability so that the county can get a return on its investment. With proper funding and action, the Outer Banks is well-suited for resilient and adaptive green infrastructure to reduce the economic and emotional impacts expected from climate change.

2. East Coast: Miami-Dade County

In Miami-Dade County, Florida, SLR is not a far-off concern, but an imminent threat. Miami-Dade, located on the southeastern tip of the state, is the most populous county in Florida, home to the city of Miami and over 2.7 million residents, the vast majority of which live less than 20 feet above sea level. The county has wide socioeconomic demographics, with Miami itself featuring a poverty rate of nearly 20% and a county rate of 15.2%, despite the area also being home to five percent of all U.S. billionaires. Additionally, Miami-Dade County’s population is home to nearly 15,000 people of color who live below three feet above sea level without SLR protection. These residents will be severely impacted by SLR, as climate models predict over two feet of SLR in Southern Florida by 2060, including SLR-related events that are anticipated to increase in both scale and quantity in the coming decades.

From 2006 to 2016, studies found that tide-induced events in the county increased by more than 400% with SLR in Southeast Florida occurring at an average rate of 9±4 mm per year, notably higher than the global average of 3±2 mm per year. Beyond the flood risk the Atlantic Ocean imposes on the coastal county, nearby bodies of water such as Biscayne Bay and the Miami River can contribute to flooding after rainfall and during storm surges. Additionally, due to the county’s proximity to sea level, the Biscayne Aquifer, which provides clean water to the vast majority of Southern Florida, is located just below ground level. With the water table so close to the surface, flooding from both tides and rainfall may have nowhere to drain after reaching land, exacerbating flood conditions. The combination of close proximity to waterways and poor drainage leaves many Miami-Dade residents living and working in areas with high flood risk. These unique conditions mean that flooding due to storm surge, rainfall, and high-tide conditions will damage property and necessary infrastructure,
pose a threat to public health and safety, and disrupt millions of lives across the county.

Over the next 30 years, an estimated 58.8% of homes in Miami-Dade County will face a major flood risk. These projections suggest that marginalized and low-income communities will bear the brunt of flooding effects, even after moving to inland areas of the county. While an early adopter of strategies aimed at developing coastal resilience and mitigating flooding, the county has concentrated investments in areas with higher-average income levels, resulting in inequitable distribution of benefits.

Beyond the risk flooding poses to communities and residential property, 19.3% of critical infrastructure facilities and 61.6% of social facilities are expected to face major flood risk in the next 30 years, while 63.4% of commercial properties are expected to face severe flood risk. By 2040, tidal inundation alone is expected to create $3.2 billion in structural losses. For Miami-Dade County, a large portion of these structural losses would stem from damage to key infrastructure systems. Saltwater intrusion from ocean flooding would threaten drinking water quality in the Biscayne Aquifer, limiting available water supplies. Additionally, with all three wastewater plants being located along the coast, flooding also poses a risk to the sewer system. When at capacity, a sewage infrastructure failure can lead to waste-filled water flooding the streets, with detrimental effects on human health.

To mitigate these climate change-induced effects, Miami-Dade County officials announced a series of plans called the Sea Level Rise Strategy (SLRS) to adapt to SLR and protect the people and property situated within the county. The plans include the intention to use a mixture of green and gray infrastructure solutions designed specifically to suit the needs of each community. The infrastructure solutions would adapt the county to a changing climate through five primary efforts: building on fill, elevating structures, funneling new development to higher ground, developing parks and living shorelines along the waterfront, and incorporating water management strategies within neighborhoods.

One of the most prominent green infrastructure solutions the county is pursuing is the development of parks and living shorelines across communities. The goal in these efforts is to maximize floodwater storage and drainage, therefore reducing the height and longevity of flooding. Structures like parks, rain gardens, and porous pavement in developed areas can absorb more water and reduce runoff. Furthermore, the development of parks, especially along the coasts, creates more space for living shorelines to thrive. In Miami-Dade County, these shorelines often take the form of salt marshes, and can be developed with the help of sills. The county is also home to mangrove wetlands, another form of living shorelines that would benefit from this additional investment into green spaces. With these additions, Miami-Dade County can increase water storage, reduce flooding, and enable biodiversity to thrive along the coasts, contributing to both long-term resilience and overall community health.

The county has allotted $1.7 billion in funding for the SLRS program so far, while noting that current studies of the impact of SLR in Miami-Dade suggest that spending may need to increase to $6.1 billion for proper SLR infrastructure. While funded projects through the program, including increasing living shorelines, raising roads, and renourishing beaches, are already underway, the implementation plans will take place over the course of five years, meaning despite installations having already occurred, updates on the effectiveness of these structures are yet to materialize.
3. West Coast: Salish Sea Region

The Salish Sea is a brackish water estuary comprising the Puget Sound located in northwest Washington State, the Strait of Georgia in British Columbia, and the Strait of Juan de Fuca between them. The surrounding landscape is characterized by the Cascadia and Coast Mountains, tidal wetlands, coniferous forests, and increasing urban development, with Vancouver to the north and Seattle to the south. The region is highly populous, with over four million people living in the U.S. counties surrounding the sound. Much of the natural habitat surrounding the Salish Sea and its river basins has been lost to development, with some habitats around the Puget Sound experiencing more than a 95% loss of marsh and estuary area.

The Pacific Northwest experiences a long wet season dominated by frequent minor precipitation events, with the occasional extreme storm. These storms, or extratropical cyclones, have caused severe damage in the past few decades. One of the most intense cyclones, the Hanukkah Eve storm of 2006, caused severe flooding and between $500 million and $1 billion 2006 USD in damage. Warming temperatures are also expected to result in decreased snowfall, with precipitation falling as rain instead and increasing winter flooding. The negative impacts of intense storms and precipitation in the Salish Sea region are likely exacerbated by the level of urbanization and extreme sea level rise. A report from the University of Washington shows that the state will likely experience about two feet of sea level rise by 2100 relative to the average sea level between 1991 and 2009. This increase in sea level is expected to increase upstream flooding as rivers will not drain into the Puget Sound as easily.

Storms and flooding also have negative impacts on the region’s water quality and coastline. During the “prolonged wet season” the region experiences high-intensity precipitation events that place stress on the region's infrastructure. Due to the urbanization of the region, this water often has few drainage options, which can contribute to prolonged flooding. This can also lead to surface runoff into rivers and contribute to wastewater discharges and sewer overflows. Due to industrial activities and developed areas in the region, flooding can cause toxins to runoff into the water supply and aquatic ecosystems. Contaminants like PCBs, PBDEs, PAHs, and metals have been found in Salish Sea fishes, with higher concentrations seen in predator species like Southern Resident Killer Whales. This can lead to development issues and health problems, particularly regarding reproduction and offspring health. In addition to impacting organisms and ecosystem health, these contaminants accumulate in fish tissue and can contribute to health issues for the many people across the Salish Sea region who consume Chinook salmon. This presents a particular threat to Indigenous communities living in the area, many of which rely on these fish and water sources in their daily lives and cultural practices.

To combat storm impacts, green stormwater infrastructure features, like green roofs, retention ponds, and permeable pavement to intercept precipitation runoff, are already fairly common in the Pacific Northwest region, and are required to be incorporated in development where feasible in western Washington. Green infrastructure policy in the Pacific Northwest is partially informed by a general culture of appreciation for the outdoors and conservation in the region. This means that while bulkheads and other hardened coastal protection measures are still used across the Puget Sound, covering about 29% of its shoreline as of August 2020, removal of these structures in favor of other shore protections has increased. This is because while these gray infrastructure solutions provide protection to the area, the disruption of sediment transport and wave reflection have exacerbated erosion in coastal regions, leading many to believe that these solutions are not viable long-term.
This mindset has fueled efforts to implement nature-based solutions across the state and projects like the Washington Coastal Resilience Project, which was a three-year effort that provided risk assessment and guidance for future shoreline stabilization efforts. One example of success in these efforts is the Smith Island Restoration Project. A setback dike restored Chinook salmon habitat in the estuary and the traditional tidal movement returned for the first time in decades. The reintroduction of the marsh estuary also proved to be beneficial for flood protection for surrounding infrastructure, including Interstate-5. Another successful effort was seen in North Cove, Washington, where the implementation of dynamic cobble revetments has resulted in erosion prevention without major disruption to the sand dynamics. The success of these projects has resulted in the desire to implement similar solutions across the region, supporting marsh restoration in the Snohomish River and restoring aquaculture efforts in Smith Cove.

The services provided by nature-based solutions in the Salish Sea are particularly important to Indigenous cultures in the region, many of which have had their traditional practices disrupted due to industrialization, pollution, and changes to the stream flow. This has resulted in efforts to work directly with tribes in restoration projects, valuing their input and traditional knowledge of the ecosystems in the area. For instance, of the 14 coastal resilience projects in Washington State recommended for funding from the BIL and IRA, nine will directly involve collaboration with tribes and/or focus on tribal priority issues. Many of these projects are aimed at protecting and restoring Chinook salmon populations, which are integral to Indigenous foodways and culture in the Pacific Northwest. NBS can help restore waterways and historical habitats and allow Chinook salmon to migrate along their traditional routes. Additionally, with less pressure on waterways and reduced flooding, lower levels of contaminants reach the Chinook salmon, making them safer for consumption. In this sense, NBS can enable a continued connection between the tribes and salmon, allowing them to continue their traditional practices, even amidst the changing environmental conditions.
Recommendations

To protect coastal communities from the effects of climate change, the Rachel Carson Council recommends prioritizing NBS rather than solely traditional gray infrastructure. Coastal communities need dynamic solutions to accommodate the unprecedented effects of climate change. While gray infrastructure solutions have historically provided temporary protection against erosion and flooding, they lack the ability to keep pace with the changing needs of their communities. Furthermore, their temporary role in hazard mitigation does not outweigh their contributions to shoreline recession. If this process is accelerated, it could exacerbate the effects of SLR and storm surges on coastal communities. This would hurt the same populations that these solutions were implemented to protect. Gray infrastructure solutions are outdated and inadequate. With the influx of recent investment in the field, it’s time to give NBS the funding they need to develop coastal resilience and support coastal communities.

The combined resources from the BIL, IRA, and BRIC provide billions of dollars to support SLR mitigation and adaptation projects. To ensure that this funding availability will translate into the NBS implementation, federal agencies need to pursue site suitability studies for NBS. Since different environments and economies impact which NBS will be most effective in an area, this work is essential to implement projects that will have the greatest benefits on their target region. Furthermore, the application process to secure this funding must prioritize NBS and actively encourage their development. In the funding allocation process, the CBA scores of NBS should be adjusted to mitigate the detrimental impact of their high discount rate and non-economic benefits to coastal and marine economies, local biodiversity, and cultural traditions. By prioritizing NBS in the scoring process, more projects will receive necessary funding and public support.

These changes to the scoring process will also help ensure that there is an equitable distribution of funding. In contrast to the current reliance on property valuation for distribution, a comprehensive approach that considers the social justice impacts of green infrastructure implementation will support more projects in disadvantaged communities. Equitable risk mitigation ensures that disadvantaged communities are protected, benefitting their property values and encouraging economic investment in their communities. It can also lower households’ NFIP rating, making flood insurance more accessible. Rather than displacement through property buyouts, the combination of protection and NFIP support ensures that disadvantaged communities can remain resilient in the face of changing conditions. However, in order for NBS to have these positive effects on disadvantaged communities, they must be implemented alongside strategies to limit climate gentrification. This can come in the form of social programs like rent control and subsidized housing or by limiting luxury residential development in protected coastal communities. With these additional programs, low-income residents will be protected by NBS, not displaced to cheaper areas with less support.

Beyond this primary funding pool to develop climate resilience, there have been millions set aside to support Tribal-run projects to restore marine ecosystems and resources. This is another way to ensure that funding distribution is accounting for factors unrepresented in the traditional CBA process. Future legislation must continue to platform Tribal knowledge and efforts. This approach is informed by an environmental justice perspective, ensuring that Tribal communities, many of which are projected to bear the brunt of SLR and storm surges in the coming years, receive the support they need to protect their communities and traditions. The RCC strongly believes that this environmental justice approach should inform every investment into coastal resilience. The most vulnerable populations are expected to be low-income and minority, and they cannot be excluded from this work. As the U.S. continues to focus on shoreline resilience, the RCC urges federal agencies to ensure that their funding is evenly distributed and supports NBS implementation across all coastal communities.
Endnotes


8 Ibid.


11 https://storymaps.arcgis.com/stories/edc3cc67b37f43a5a815202f81768911.


15 Ibid.

16 Ibid.


19 Gittman et al. “Marshes With and Without Sills Protect Estuarine Shorelines from Erosion Better than Bulkheads During a Category 1 Hurricane.”


Ibid.


Currin.
45 Curran; Gedan et al.
46 Ibid.
61 Paul.


“Coastal Blue Carbon.”


Reeder-Myers et al., “Indigenous Oyster Fisheries Persisted for Millenia and Should Inform Future Management.”


Rodriguez et al., “Oyster Reefs Can Outpace Sea-Level Rise.”


Ibid.


Ibid.

Ibid.


Ibid.


Ibid.


Ibid.


Ibid.

Ibid.

Ibid.

Ibid.


Stewart-Sinclair et al., “Spatial Cost–Benefit Analysis of Blue Restoration and Factors Driving Net Benefits Globally.”


Ibid.

Ibid.


Ibid.


Keenan & Siders.


Han Li and Richard J. Grant, “Climate Gentrification in Miami: A Real Climate Change–Minded Investment Practice?,” Cities 131 (December 1, 2022): 104025, https://doi.org/10.1016/j.cities.2022.104025


140 Reeder-Myers et al., “Indigenous Oyster Fisheries Persisted for Millennia and Should Inform Future Management.”


142 “Tribal Nations.”


154 “Sinking Tax Base: Land & Property at Risk from Rising Seas” (Princeton, NJ: Climate Central, September 8, 2022), https://assets.ctfassets.net/cxgxgstp8r5d/2KKeTjnqbFelWrZalnPeRR/9a28719038f3a1dddbdd2e8b78b8455b/CC_Sinking_Tax_Base_20220908a.pdf.

155 Ibid.


162 “Sea Level Rise Viewer.”
165 Dennis, “Retreat in Rodanthe.”
167 Ibid.
176 Gittman et al., “Marshes with and without sills protect estuarine shorelines from erosion better than bulkheads during a Category 1 hurricane.”
177 Ibid.
181 Gregg and Braddock, “Alligator River National Wildlife Refuge/Albemarle-Pamlico Peninsula Climate Adaptation Project.”


184 Flavelle and Mazzei, “Miami Says It Can Adapt to Rising Seas. Not Everyone Is Convinced.”


190 “Flood Risk Overview: Does Miami-Dade County Have Flood Risk?”


192 “Sea Level Rise and Flooding.”


198 “Puget Sound Trends” (Seattle, WA: Puget Sound Regional Council, December 2020), https://www.psrc.org/media/7275#:~:text=The%20population%20of%20the%20four,growth%20from%20people%20moving%20here.


208 Jayakaran et al., “Green Infrastructure in Western Washington and Oregon.”

210 Ibid.


216 Ibid.


The Rachel Carson Council is the national environmental organization envisioned by Rachel Carson and founded in 1965 to carry on her work after her death. We promote Carson’s ecological ethic that combines scientific concern for the environment and human health with a sense of wonder and reverence for all forms of life in order to build a sustainable, just, and peaceful future.

The Rachel Carson Campus Network (RCCN) links students, faculty, staff, and administrators at campuses nationwide to the Rachel Carson Council to provide and share information and resources, recruit environmental leaders, and work on and off campus to create lasting changes in policy and practice for a sustainable future.