Tides Up

Nature-Based Solutions for Sea Level Rise

RACHEL CARSON COUNCIL

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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.[1] *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.[2] 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.[3] 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.[4] 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.[5] 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.

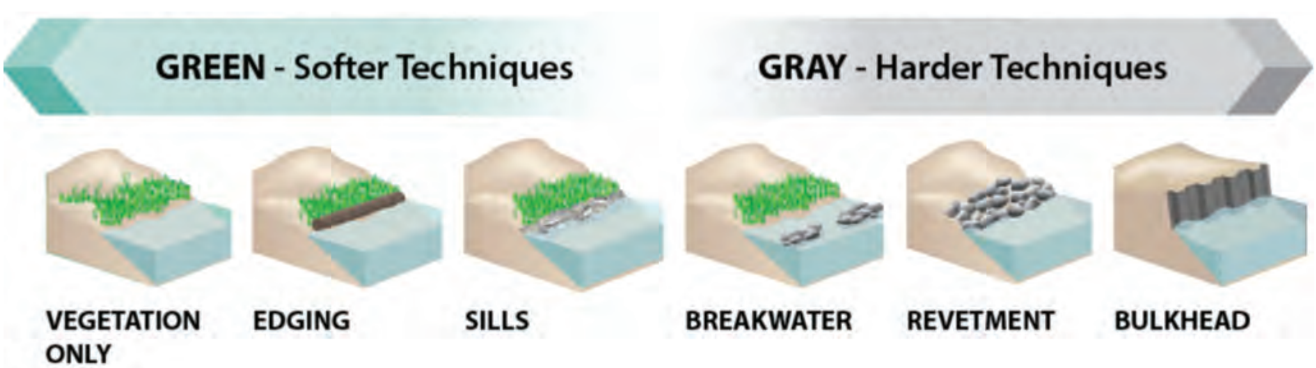


Figure adapted from Congressional Research Service, Nature-Based Infrastructure: NOAA's Role, 2020, p. 3, at https://www.everycrsreport.com/files/20200102_R46145_6027ea5c62df4c4a03a2570fcaac97a6906d49ec.pdf.

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.[6] 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.[7] 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.[8] 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

market. Coastal ecosystems have a high capacity for carbon storage and sequestration, absorbing carbon dioxide ten times faster than forests.[9] Companies, individuals, or other organizations can purchase carbon credits to offset their emissions, and this investment often funds conservation efforts.[10] 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.[11] 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.[12] 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.[13] 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.[14] These impermeable structures are placed parallel to shore and aim to prevent the slide of land or sediment into the ocean.[15] 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.[16] 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.[17] 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.[18] 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.[19] Similarly, in New Jersey, bulkheads and seawalls have struggled to keep pace with rising sea levels, rendering them less effective than nature-based solutions.[20]

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.[21] 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.[22] 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.[23] 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.[24] 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.[25] 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.[26] 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.[27] 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.[28] 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.[29] 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.[30] 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.[31] During storms, these resilient marshes absorb and distribute incoming wave energy and water across dense vegetation and sediment.[32] 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.[33] Over 15% of the coast is classified as wetlands, an area which constitutes about 40 million acres.[34] Wetlands host an immense level of biodiversity, providing habitat for 40% of all species.[35] 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.[36] An extensive body of research suggests that coastal wetlands provide protections from floods during severe storms.[37] 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.[38] Mangrove forests, a type of wetland consisting mainly of trees and shrubs typically found in subtropical and tropical brackish water estuaries,[39] have also been found to reduce water levels during storm surge on the Gulf Coast of Florida during hurricanes in 2004 and 2005.[40]

Marsh plants like cordgrasses increase friction against wave energy, reducing the rate at which water moves across the landscape.[41] This absorption of wave energy reduces erosion and property damage.[42] In 2015, research at the mouth of the Chesapeake Bay determined that a primarily cordgrass marsh reduced wave energy during two coastal storms.[43] 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.[44] The efficacy of wetlands for wave attenuation depends on various factors, including vegetation height and density, wave height, and the strength of the wave.[45]

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.[46] 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.[47]

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.[48] 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.[49]

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%.[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.[51]

In addition to providing flood and wave attenuation, mangroves act as strong wind buffers, reducing wave formation.[52] 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.[53]

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.[54] 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.[55] 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.[56]

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.[57] 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.[58]

Like other wetlands, seagrass meadows stabilize and accumulate sediment and reduce wave energy.[59] Both tall and short seagrasses can accumulate sediment by slowing the movement of water and allowing sediments to settle, including fine particles.[60] 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.[61] 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.[62] 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.[63]

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.[64] Similarly, the Tampa Bay Estuary Program has restored more than 40,000 acres of seagrasses between

1991 and 2015.[65] 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.[66] 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.[67]

While numerous studies have found positive effects of seagrasses on shoreline protection, there remain significant knowledge gaps due to a lack of research[68] and mixed findings from existing studies.[69] 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.[70] Seagrass meadows specifically hold about 5% of global carbon dioxide.[71]

Additionally, evidence shows that coastal wetlands sequester 10 times more carbon each year than mature tropical forests.[72]

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.[73] 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.[74] 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.[75] 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.[76]

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.[77] One study found that the reefs may "match even the highest predictions of SLR by the year 2100."[78] 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.[79]

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.[80] 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.[81]

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.[82] 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.[83]

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.[84] Additionally, SLR remains an existential threat toward these reefs, as intertidal oysters grow 34% faster and more voluminous than their subtidal counterparts,[85] 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.[86] 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.[87] The tempering effect of reef systems on wave energy also reduces the size of potential flood plains in coastal communities.[88] 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.[89] Similar studies in South Florida and the U.S. Virgin Islands have correlated similar benefits from reef conservation.[90] 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.[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.[92] Projections anticipate an increase of 263% in Puerto Rico, 127% in American Samoa, and 120% in the U.S. Virgin Islands.[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.[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.[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).[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.[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.

SOCIOECONOMIC AND ENVIRONMENTAL JUSTICE IMPLICATIONS

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.[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.[106] The West Coast also faces severe SLR risks, with a projected SLR of seven feet before 2100 in the Bay Area, California.[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.[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.[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.[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.[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.[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.[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.[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.[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.[116] 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.[117] 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.[118] 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.[119]

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.[120] 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.[121]

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.[122] 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.[123] 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%.[124] 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.[125]

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.[126] 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.[127] 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.[128] 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.[129] 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.[130]

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.[131] 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.[132] 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.[133] 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.[134]

When shoreline stabilization programs are implemented without comprehensive consideration, they can force the migration of pre-existing communities and leave marginalized populations vulnerable.[135] 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.[136] 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.[137] Additionally, SLR threatens the tribe's ancestral burial grounds.[138] 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.[139] 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.[140]

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.[141] 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.[142] 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.[143]

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.[144] 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.[145]

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.[146]

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.[147] 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.[148] 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.[149] 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.[150] 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.[151] 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.[152]

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.[153] 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.[154] 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.[155] 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.[156] Additionally, the section discusses the adaptation strategies already in place in these locations, as well as possible investments specific to the landscapes.

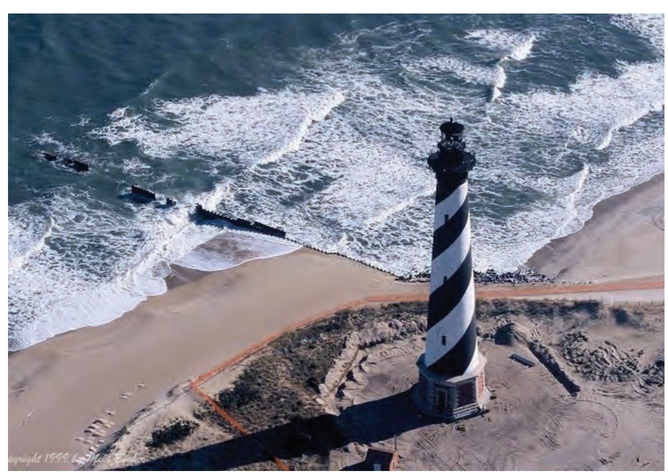
1. East Coast: Dare County

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.[157] 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.[158] 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.[159] 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.[160]

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.[161] 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.[162] 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.[163] 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.[164]

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.[165] 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.[166] 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.[167]



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.[168] 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.[169] As flooding and property collapsing persists, many OBX communities have turned to adaptation measures.[170]

Erosion is a natural process for barrier islands,[171] 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.[172] 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.[173] 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.[174] 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.[175] 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.[176] 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.[177] 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.[178] 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.[179] 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.[180] 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.[181] 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.[182] 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.[183] 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.[184]

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.[185] 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.[186] 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.[187] 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.[188] 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.[189]

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.[190] By 2040, tidal inundation alone is expected to create $3.2 billion in structural losses.[191] 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.[192] 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.[193] 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.[194] 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.[195] 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.[196]

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.[197] 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.[198] 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.[199]

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.[200] Warming temperatures are also expected to result in decreased snowfall, with precipitation falling as rain instead and increasing winter flooding.[201] 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.[202] This increase in sea level is expected to increase upstream flooding as rivers will not drain into the Puget Sound as easily.[203]

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.[204] 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.[205] 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.[206] 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.[207]

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.[208] Green infrastructure policy in the Pacific Northwest is partially informed by a general culture of appreciation for the outdoors and conservation in the region.[209] 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.[210] 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.[211] 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.[212] 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.[213] 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.[214] 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.[215] 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.[216] 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.[217] 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.[218] 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

1 Kendall Jefferys, "An Ocean of Climate Solutions," *Rachel Carson Council* (blog), accessed September 22, 2023, https://rachelcarsoncouncil.org/ocean-climate-solutions/.

2 "Is the Rate of Sea-Level Rise Increasing?," NASA Sea Level Change Portal, accessed September 22, 2023, https://sealevel.nasa.gov/faq/8/is-the-rate-of-sea-level-rise-increasing.

3 Angela Colbert, "A Force of Nature: Hurricanes in a Changing Climate," NASA Global Climate Change, June 1, 2022, https://climate.nasa.gov/news/3184/a-force-of-nature-hurricanes-in-a-changing-climate; "How Climate Change Makes Hurricanes More Destructive," Environmental Defense Fund, accessed September 22, 2023, https://www.edf.org/climate/how-climate-change-makes-hurricanes-more-destructive.

4 "How Long Is the U.S. Shoreline?," National Ocean Service, August 8, 2023, https://oceanservice.noaa.gov/facts/shorelength.html.

5 "Reading: Human Modifications of Coastal Processes," Lumen Geology, accessed June 8, 2023, https://courses.lumenlearning.com/geo/chapter/reading-human-modifications-of-coastal-processes/.

6 "Green and Gray Infrastructure Research," Overviews and Factsheets, United States Environmental Protection Agency, February 7, 2023, https://www.epa.gov/water-research/green-and-gray-infrastructure-research.

7 William Nardin, Jonathan Leathers, and Iacopo Vona, "Integrating Oyster Castles into Living Shorelines to Promote Coastal Bays Resilience to Sea Level Rise," *Authorea Preprints*, 2022; Rachel K. Gittman et al., "Marshes with and without Sills Protect Estuarine Shorelines from Erosion Better than Bulkheads during a Category 1 Hurricane," *Ocean & Coastal Management* 102 (December 1, 2014): 94–102, https://doi.org/10.1016/j.ocecoaman.2014.09.016; Carter S. Smith et al., "Living Shorelines Enhanced the Resilience of Saltmarshes to Hurricane Matthew (2016)," *Ecological Applications* 28, no. 4 (2018): 871–77, https://doi.org/10.1002/eap.1722; Carolyn Currin, "Living Shorelines for Coastal Resilience," in *Coastal Wetlands, Second Edition: An Integrated and Ecosystem Approach*, ed. Gerardo M.E. Perillo et al. (Elsevier, 2019), 1023–53, https://doi.org/10.1016/B978-0-444-63893-9.00030-7.

8 Ibid.

9 "Coastal Blue Carbon," National Ocean Service, accessed September 22, 2023, https://oceanservice.noaa.gov/podcast/feb15/os6-bluecarbon.html.

10 Nicola Jones, "Why the Market for 'Blue Carbon' Credits May Be Poised to Take Off," Yale Environment 360, April 13, 2021, https://e360.yale.edu/features/why-the-market-for-blue-carbon-credits-may-be-poised-to-take-off.

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

12 "NOAA Tribal Resources & Updates," National Oceanic and Atmospheric Administration, February 28, 2022, https://www.noaa.gov/legislative-and-intergovernmental-affairs/noaa-tribal-resources-updates.

13 Erin Blakemore, "Over 14,000 Miles of America's Coastline Is Covered in Concrete," *Smithsonian Magazine*, August 21, 2015, https://www.smithsonianmag.com/smart-news/scientists-are-warning-against-concrete-coated-beaches-180956359/.

14 "Bulkheads and Shoreline Stabilization" (Seattle, WA: King County Department of Natural Resources and Parks), accessed September 25, 2023, https://your.kingcounty.gov/dnrp/library/water-and-land/shorelines/0709-fact-sheets/Bulkheads.pdf.

15 Ibid.

16 Ibid.

17 Sean Cornell et al., "Coastal Processes, Hazards, and Society: Seawalls," Interdisciplinary Teaching about Earth for a Sustainable Future, accessed September 23, 2023, https://www.e-education.psu.edu/earth107/node/1062.

18 Carter S. Smith et al., "Hurricane Damage along Natural and Hardened Estuarine Shorelines: Using Homeowner Experiences to Promote Nature-Based Coastal Protection," *Marine Policy* 81 (July 1, 2017): 350–58, https://doi.org/10.1016/j.marpol.2017.04.013.

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

20 Jon K. Miller et al., "Living Shorelines Engineering Guidelines" (Hoboken, NJ: Stevens Institute of Technology, February 2016), https://www.nj.gov/dep/cmp/docs/living-shorelines-engineering-guidelines-final.pdf.

21 Rachel K. Gittman et al., "Ecological Consequences of Shoreline Hardening: A Meta-Analysis," *BioScience* 66, no. 9 (September 1, 2016): 763–73, https://doi.org/10.1093/biosci/biw091.

22 "Coastal Flood Defences: Revetments" (Newground, September 2021), https://thefloodhub.co.uk/wp-content/uploads/2018/09/Revetments.pdf.
23 "Impermeable Revetments," RISC-KIT, accessed September 23, 2023, https://www.coastal-management.eu/impermeable-revetments.html.
24 "Seawalls, Bulkheads, and Revetments," National Park Service, April 5, 2019, https://www.nps.gov/articles/seawalls-bulkheads-and-revetments.htm.
25 Jonathan C. Allan, Ron Geitgey, and Roger Hart, "Dynamic Revetments for Coastal Erosion in Oregon" (Newport, OR: Oregon Department of Geology and Mineral Industries, August 2005), https://www.oregon.gov/odot/Programs/ResearchDocuments/DynamicRevetments.pdf.
26 "Offshore Breakwaters & Beach Nourishment," Virginia Institute of Marine Science, accessed September 25, 2023, https://www.vims.edu/ccrm/outreach/living_shorelines/design/sills_breakwaters/breakwaters/index.php.
27 Nathan Kensinger, "Photos: NY Begins Construction On $107 Million 'Living' Barriers To Fight The City's Rising Seas," *Gothamist*, November 12, 2021, sec. News, https://gothamist.com/news/photos-ny-begins-construction-on-107-million-living-barriers-to-fight-the-citys-rising-seas.
28 "Solution: Living Breakwaters" (Naturally Resilient Communities, n.d.), accessed September 25, 2023.
29 "Artificial Reefs Create Homes for Sea Life," *U.S. Department of the Interior* (blog), June 25, 2018, https://www.doi.gov/blog/artificial-reefs-create-homes-sea-life.
30 "Living Shorelines: Design Options - Marsh Sill with Planted Marsh," Center for Coastal Resources Management, accessed September 25, 2023, http://ccrm.vims.edu/livingshorelines/design_options/marsh_sill_planted.html.
31 Mackenzie Taggart and Brandon Puckett, "Living Storm Protections: Part II," Albemarle-Pamlico National Estuary Partnership, February 14, 2019, https://apnep.nc.gov/blog/2019/02/14/living-storm-protections-part-ii.
32 Ibid.
33 "About Coastal Wetlands," United States Environmental Protection Agency, January 28, 2023, https://www.epa.gov/wetlands/about-coastal-wetlands.
34 "Land Cover Change," Office for Coastal Management, accessed June 12, 2023, https://coast.noaa.gov/states/fast-facts/land-cover-change.html; "About Coastal Wetlands."
35 "Call for an Ambitious Global Biodiversity Framework on World Wetlands Day 2020," IUCN, January 31, 2020, https://www.iucn.org/news/water/202001/call-ambitious-global-biodiversity-framework-world-wetlands-day-2020.
36 M. Acreman and J. Holden, "How Wetlands Affect Floods," *Wetlands* 33, no. 5 (October 1, 2013): 773–86, https://doi.org/10.1007/s13157-013-0473-2.
37 E.g., Christine C. Shepard, Caitlin M. Crain, and Michael W. Beck, "The Protective Role of Coastal Marshes: A Systematic Review and Meta-Analysis," *PLOS ONE* 6, no. 11 (November 23, 2011): e27374, https://doi.org/10.1371/journal.pone.0027374; Siddharth Narayan et al., "The Value of Coastal Wetlands for Flood Damage Reduction in the Northeastern USA," *Scientific Reports* 7, no. 1 (August 31, 2017): 9463, https://doi.org/10.1038/s41598-017-09269-z.
38 Y. Peter Sheng et al., "Role of Wetlands in Reducing Structural Loss Is Highly Dependent on Characteristics of Storms and Local Wetland and Structure Conditions," *Scientific Reports* 11, no. 1 (March 4, 2021): 5237, https://doi.org/10.1038/s41598-021-84701-z.
39 "Mangrove Swamps," Overviews and Factsheets, United States Environmental Protection Agency, September 30, 2022, https://www.epa.gov/wetlands/mangrove-swamps.
40 Ken W. Krauss et al., "Water Level Observations in Mangrove Swamps during Two Hurricanes in Florida," *Wetlands* 29, no. 1 (March 1, 2009): 142–49, https://doi.org/10.1672/07-232.1.
41 Currin; Keryn B. Gedan et al., "The Present and Future Role of Coastal Wetland Vegetation in Protecting Shorelines: Answering Recent Challenges to the Paradigm," *Climatic Change* 106 (2011): 7–29, https://doi.org/10.1007/s10584-010-0003-7.
42 R. A. Feagin et al., "Does Vegetation Prevent Wave Erosion of Salt Marsh Edges?," *Proceedings of the National Academy of Sciences* 106, no. 25 (June 23, 2009): 10109–13, https://doi.org/10.1073/pnas.0901297106.
43 Anne-Eleonore Paquier et al., "Quantification of the Attenuation of Storm Surge Components by a Coastal Wetland of the US Mid Atlantic," *Estuaries and Coasts* 40, no. 4 (July 1, 2017): 930–46, https://doi.org/10.1007/s12237-016-0190-1.
44 Currin.

45 Currin; Gedan et al.
46 Ibid.
47 Katrina L. Poppe and John M. Rybczyk, "Tidal Marsh Restoration Enhances Sediment Accretion and Carbon Accumulation in the Stillaguamish River Estuary, Washington," *PLOS ONE* 16, no. 9 (September 10, 2021): e0257244, https://doi.org/10.1371/journal.pone.0257244.
48 "Wetlands," Reports and Assessments, United States Environmental Protection Agency, March 29, 2023, https://www.epa.gov/report-environment/wetlands.
49 "What Is Eutrophication?," National Ocean Service, January 20, 2023, https://oceanservice.noaa.gov/facts/eutrophication.html; Emma Brentjens, "Wetlands or Wastelands?," *Rachel Carson Council* (blog), accessed September 22, 2023, https://rachelcarsoncouncil.org/wetlands-or-wastelands/.
50 F. Y. Cheng et al., "Maximizing US Nitrate Removal through Wetland Protection and Restoration," *Nature* 588, no. 7839 (December 2020): 625–30, https://doi.org/10.1038/s41586-020-03042-5.
51 Erin Conlisk et al., "Evidence for Multiple Benefits of Wetland Conservation in North America: Carbon, Biodiversity, and Beyond" (Petaluma, CA: Point Blue Conservation Science, December 2022), https://www.nrdc.org/sites/default/files/evidence-multiple-benefits-wetlands-conservation-report-202301.pdf.
52 Mark Spalding et al., "Mangroves for Coastal Defence. Guidelines for Coastal Managers & Policy Makers" (Wageningen, NL: Wetlands International, 2014), https://www.nature.org/media/oceansandcoasts/mangroves-for-coastal-defence.pdf.
53 Stijn Temmerman et al., "Marshes and Mangroves as Nature-Based Coastal Storm Buffers," *Annual Review of Marine Science* 15 (2023): 95–118, https://doi.org/10.1146/annurev-marine-040422-092951.
54 "Large Scale Wetland Restoration (NRCS)," North Carolina Coastal Federation, accessed September 22, 2023, https://www.nccoast.org/project/nrcs/.
55 "Restoring Wetlands," National Park Service, accessed September 22, 2023, https://www.nps.gov/subjects/wetlands/restoring-wetlands.htm.
56 "Comprehensive Everglades Restoration Plan (CERP)," National Park Service, May 19, 2022, https://www.nps.gov/ever/learn/nature/cerp.htm.
57 Pamela L. Reynolds, "Seagrass and Seagrass Beds," Smithsonian Ocean, April 30, 2018, https://ocean.si.edu/ocean-life/plants-algae/seagrass-and-seagrass-beds.
58 Reynolds, "Seagrass and Seagrass Beds;" "Importance of Seagrasses," Florida Museum, October 3, 2018, https://www.floridamuseum.ufl.edu/southflorida/habitats/seagrasses/importance/.
59 "Importance of Seagrass," Florida Fish And Wildlife Conservation Commission, accessed September 23, 2023, https://myfwc.com/research/habitat/seagrasses/information/importance/; "Seagrass—Secret Weapon in the Fight against Global Heating," United Nations Environment Programme, November 1, 2019, http://www.unep.org/news-and-stories/story/seagrass-secret-weapon-fight-against-global-heating.
60 Maike Paul, "The Protection of Sandy Shores – Can We Afford to Ignore the Contribution of Seagrass?," *Marine Pollution Bulletin*, Securing a future for seagrass, 134 (September 1, 2018): 152–59, https://doi.org/10.1016/j.marpolbul.2017.08.012.
61 Paul.
62 United Nations Environment Programme, "Out of the Blue: The Value of Seagrasses to the Environment and to People" (Nairobi, KE: UNEP, 2020).
63 "Seagrass Restoration," Duke Nicholas Institute, accessed June 13, 2023, https://nicholasinstitute.duke.edu/eslm/seagrass-restoration.
64 Reynolds, "Seagrass and Seagrass Beds;" "Seagrass Restoration," Virginia Institute of Marine Science, n.d., https://www.vims.edu/research/units/programs/sav1/restoration/index.php.
65 Hannah Waters, "Bringing Back Tampa Bay's Seagrass," Smithsonian Ocean, January 2017, https://ocean.si.edu/ocean-life/plants-algae/bringing-back-tampa-bays-seagrass.
66 Marieke M. van Katwijk et al., "Global Analysis of Seagrass Restoration: The Importance of Large-Scale Planting," *Journal of Applied Ecology* 53, no. 2 (2016): 567–78, https://doi.org/10.1111/1365-2664.12562; United Nations Environment Programme.
67 Letitia Stein, "In Tampa Bay, Rare Environmental Win Measured in Seagrass," *Reuters*, June 9, 2015, sec. Environment, https://www.reuters.com/article/us-usa-environment-tampabay-idUSKBN0OP13Z20150609.

68 Carter S. Smith et al., "Coming to Terms With Living Shorelines: A Scoping Review of Novel Restoration Strategies for Shoreline Protection," *Frontiers in Marine Science* 7 (2020), https://www.frontiersin.org/articles/10.3389/fmars.2020.00434.
69 E.g., Mariko A. Polk and Devon O. Eulie, "Effectiveness of Living Shorelines as an Erosion Control Method in North Carolina," *Estuaries and Coasts* 41, no. 8 (December 1, 2018): 2212–22, https://doi.org/10.1007/s12237-018-0439-y.
70 A. M. Nahlik and M. S. Fennessy, "Carbon Storage in US Wetlands," *Nature Communications* 7, no. 1 (December 13, 2016): 13835, https://doi.org/10.1038/ncomms13835.
71 Tatiana Schlossberg, "A Powerful Climate Solution Just Below the Ocean's Surface," *The New York Times*, May 24, 2023, sec. Climate, https://www.nytimes.com/2023/05/24/climate/seagrass-climate-change.html.
72 "Coastal Blue Carbon."
73 "Summary for Policymakers of IPCC Special Report on Global Warming of 1.5°C Approved by Governments," IPCC, October 8, 2018, https://www.ipcc.ch/2018/10/08/summary-for-policymakers-of-ipcc-special-report-on-global-warming-of-1-5c-approved-by-governments/.
74 Leslie Reeder-Myers et al., "Indigenous oyster fisheries persisted for millenia and should inform future management," *Nature Communications* 13, no. 2383 (May 2022), https://doi.org/10.1038/s41467-022-29818-z; Sydney Giuliano, "Shell-tering our shores from sea level rise," *U.S. Fish & Wildlife Service*, August 4, 2022, https://www.fws.gov/story/2022-08/shell-tering-our-shores-sea-level-rise.
75 Emily Matchar, "As Storms Get Bigger, Oyster Reefs Can Help Protect Shorelines," *Smithsonian Magazine*, January 10, 2018, https://www.smithsonianmag.com/innovation/storms-get-bigger-oyster-reefs-can-help-protect-shorelines-180967774/.
76 Thomas Dunlop, "Optimal Oyster Reef Design for Shoreline Protection Using Combinations of Oyster Shell Filled Bags and Sandbags" (Sydney, AU, University of New South Wales, 2016), https://www.wrl.unsw.edu.au/sites/wrl/files/uploads/Projects/2016_Optimal_Oyster_Reef_Design_for_Shoreline_Protection.pdf; Ossmann, "A New Shoreline Uses Oyster Castles to Shield a Community," Chesapeake Bay Program, February 19, 2020, https://www.chesapeakebay.net/news/blog/a-new-shoreline-uses-oyster-castles-to-shield-a-community; Katie Mosher, "A New Spat-On-Shell Demonstration Project," Coastwatch Currents, July 23, 2020, https://ncseagrant.ncsu.edu/currents/2020/07/spat-on-shell-demonstration-project-will-benefit-oyster-harvests-and-coastal-ecosystems/.
77 Patricia L. Wilberg et al., "Wave Attenuation by Oyster Reefs in Shallow Coastal Bays," *Estuaries and Coasts* 42, 331-347 (2019), https://doi.org/10.1007/s12237-018-0463-y.
78 Antonio B. Rodriguez et al., "Oyster reefs can outpace sea-level rise," *Nature Climate Change* 4, 493-497 (2014), https://doi.org/10.1038/nclimate2216.
79 F. Joel Fodrie et al., "Oyster reefs as carbon sources and sinks," *The Royal Society* (July 2017), https://doi.org/10.1098/rspb.2017.0891.
80 "Oyster Reef Habitat," NOAA Fisheries, February 4, 2022, National, https://www.fisheries.noaa.gov/national/habitat-conservation/oyster-reef-habitat.
81 "Oyster Reefs," Indian River Lagoon Species Inventory, accessed September 22, 2023, https://irlspecies.org/misc/Oyster_reef.php.
82 Alice H. Howie and Melanie J. Bishop, "Contemporary Oyster Reef Restoration: Responding to a Changing World," *Frontiers in Ecology and Evolution* 9 (2021), https://www.frontiersin.org/articles/10.3389/fevo.2021.689915.
83 Reeder-Myers et al., "Indigenous Oyster Fisheries Persisted for Millennia and Should Inform Future Management."
84 Michael W. Beck et al., "Oyster Reefs at Risk and Recommendations for Conservation, Restoration, and Management," *Bioscience* 61, no. 2 (2011): 107–16.
85 Rodriguez et al., "Oyster Reefs Can Outpace Sea-Level Rise."
86 "The Economic Value of U.S. Coral Reefs" (Silver Spring, MD: NOAA Coral Reef Conservation Program, 2013), https://www.ncei.noaa.gov/data/oceans/coris/library/NOAA/CRCP/other/other_crcp_publications/Economic_Value_US_Coral_Reefs_Summary_2013.pdf.
87 Borja G. Reguero et al., "The Value of US Coral Reefs for Flood Risk Reduction," *Nature Sustainability* 4, no. 8 (2021): 688–98.
88 Ibid.
89 "Mapping the Risk Reduction Benefits of Coral Reef Conservation," FEMA Hazus Success Story (Washington, D.C.: Federal Emergency Management Agency, May 2021), https://www.fema.gov/sites/default/files/documents/fema_hazus-success-story-coral-reef.pdf.

90 Lauren T. Toth et al., "The Potential for Coral Reef Restoration to Mitigate Coastal Flooding as Sea Levels Rise," *Nature Communications* 14, no. 1 (2023): 2313.
91 Reguero et al., "The value of US coral reefs for flood risk reduction."
92 Ibid.
93 Ibid.
94 Tim Stephens, "From The University of California-Santa Cruz: 'Reefense Project Aims to Meld Biology and Engineering in Novel Structures for Coastal Protection,'" *Sciencesprings* (blog), June 22, 2022, https://sciencesprings.wordpress.com/2022/06/23/from-the-university-of-california-santa-cruz-reefense-project-aims-to-meld-biology-and-engineering-in-novel-structures-for-coastal-protection/.
95 "Artificial Reefs," Florida Keys National Marine Sanctuary, accessed October 16, 2023, https://floridakeys.noaa.gov/artificialreefs/welcome.html.
96 "NOAA Coral Reef Conservation Program," National Oceanic and Atmospheric Administration, accessed October 16, 2023, https://coralreef.noaa.gov/.
97 Ibid.
98 "Coastal Economy Data," National Ocean Economics Program, accessed October 16, 2023, https://www.oceaneconomics.org/NOEP/Market/coastal/coastalEcon.asp.
99 "Ocean Economy and Innovation," Organisation for Economic Co-operation and Development, accessed June 12, 2023, https://www.oecd.org/ocean/topics/ocean-economy/#.
100 "NOAA Report on the U.S. Marine Economy," (Charleston, SC: NOAA Office for Coastal Management, 2022), https://coast.noaa.gov/data/digitalcoast/pdf/econ-report.pdf.
101 Ibid.
102 Noah S. Diffenbaugh and Elizabeth A. Barnes, "Data-Driven Predictions of the Time Remaining until Critical Global Warming Thresholds Are Reached," *Proceedings of the National Academy of Sciences* 120, no. 6 (February 7, 2023): e2207183120, https://doi.org/10.1073/pnas.2207183120.
103 Will Kenton, "Labor Intensive: Definition and Examples," Investopedia, November 28, 2020, https://www.investopedia.com/terms/l/laborintensive.asp; Ravi Bansal, Dana Kiku, and Marcelo Ochoa, "What Do Capital Markets Tell Us About Climate Change?," *Society for Economic Dynamics*, Meeting Papers 542 (2016), https://ideas.repec.org/p/red/sed016/542.html.
104 Ravi Bansal, Dana Kiku, and Marcelo Ochoa, "What Do Capital Markets Tell Us About Climate Change?"
105 James E. Neumann et al., "Joint effects of storm surge and sea-level rise on US Coasts: new economic estimates of impacts, adaptation, and benefits of mitigation policy," *Climatic Change* 129, 337–349 (2015), https://doi.org/10.1007/s10584-014-1304-z.
106 "Rapid Sea Level Rise along the U.S. East and Gulf Coasts during 2010-2022 and Its Impact on Hurricane-Induced Storm Surge," *Climate Program Office*, March 30, 2023, https://cpo.noaa.gov/Rapid-Sea-Level-Rise-along-the-US-East-and-Gulf-Coasts-during-2010-2022-and-Its-Impact-on-Hurricane-Induced-Storm-Surge/#:~:text=The%20faster%20SLR%20on%20the,particularly%20on%20the%20Gulf%20Coast; "Natural Disasters: Economic Effects of Hurricanes Katrina, Sandy, Harvey, and Irma," *U.S. Government Accountability Office*, September 10, 2020, https://www.gao.gov/products/gao-20-633r.
107 Sarah Cafasso, "Stanford researchers map how sea-level rise adaptation strategies impact economies and floodwaters," *Stanford News*, July 12, 2021, https://news.stanford.edu/2021/07/12/economic-impacts-combatting-sea-level-rise/.
108 NOAA, "What Percentage of the American Population Lives near the Coast?," National Ocean Service, January 20, 2023, https://oceanservice.noaa.gov/facts/population.html.
109 Ibid.
110 Kristen Crosset et al., "National Coastal Population Report: Population Trends from 1970 to 2020" (Washington, DC: National Oceanic and Atmospheric Administration, March 2013), https://aambpublicoceanservice.blob.core.windows.net/oceanserviceprod/facts/coastal-population-report.pdf.
111 Ibid.
112 Ibid.
113 Ibid.
114 Ibid.

115 EPA, "Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts" (Washington, DC: EPA Office of Atmospheric Programs, September 2021), https://www.epa.gov/system/files/documents/2021-09/climate-vulnerability_september-2021_508.pdf.
116 J.A.G. Cooper et al., "The adaptation-resistance spectrum: A classification of contemporary adaptation approaches to climate-related coastal change," *Ocean & Coastal Management* 94 (2014): 90-98, http://doi.org/10.1016/j.ocecoaman.2013.09.006.
117 Phoebe J. Stewart-Sinclair et al., "Spatial Cost–Benefit Analysis of Blue Restoration and Factors Driving Net Benefits Globally," *Conservation Biology* 35, no. 6 (2021): 1850–60, https://doi.org/10.1111/cobi.13742.
118 "Fisheries Economics of the United States, 2020 Report," NOAA Fisheries, February 17, 2023, National, https://www.fisheries.noaa.gov/resource/document/fisheries-economics-united-states-2020-report.
119 Stewart-Sinclair et al., "Spatial Cost–Benefit Analysis of Blue Restoration and Factors Driving Net Benefits Globally."
120 Borja G. Reguero et al., "Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States," *PLOS One* (2018), https://doi.org/10.1371/journal.pone.0192132.
121 Ibid.
122 Ibid.
123 "Mapping Social Vulnerability in Southeastern States and the Gulf Coast," Oxfam, accessed September 22, 2023, https://www.oxfamamerica.org/explore/countries/united-states/poverty-in-the-us/mapping-social-vulnerability-in-southeastern-states-and-the-gulf-coast/.
124 "Race and Ethnicity in Mississippi (State)," Statistical Atlas, accessed September 22, 2023, https://statisticalatlas.com/state/Mississippi/Race-and-Ethnicity.
125 Ibid.
126 A. R. Siders and Jesse M. Keenan, "Variables Shaping Coastal Adaptation Decisions to Armor, Nourish, and Retreat in North Carolina," *Ocean & Coastal Management* 183 (January 1, 2020): 105023, https://doi.org/10.1016/j.ocecoaman.2019.105023
127 Jake Bittle, "How FEMA's Flood Buyout Program Enables White Flight," Grist, June 16, 2023, https://grist.org/housing/fema-flood-buyout-study-managed-retreat-segregation/.
128 Diane P. Horn, "Flood Buyouts: Federal Funding for Property Acquisition" (Congressional Research Service, April 8, 2022), https://crsreports.congress.gov/product/pdf/IN/IN11911.
129 Katherine Bagley, "Equitable Retreat: The Need for Fairness in Relocating Coastal Communities," Yale Environment 360, November 19, 2020, https://e360.yale.edu/features/equitable-retreat-the-need-for-fairness-in-relocating-coastal-communities.
130 Keenan & Siders.
131 "Green Gentrification," Barcelona Laboratory for Urban Environmental Justice and Sustainability, accessed September 23, 2023, https://www.bcnuej.org/green-gentrification/.
132 Kriston Capps and Christopher Cannon, "Redlined, Now Flooding," March 15, 2021, https://www.bloomberg.com/graphics/2021-flood-risk-redlining/.
133 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
134 Thomas Frank, "Flooding Disproportionately Harms Black Neighborhoods," *Scientific American*, June 2, 2020, https://www.scientificamerican.com/article/flooding-disproportionately-harms-black-neighborhoods/
135 Christopher Flavelle and Patricia Mazzei, "Miami Says It Can Adapt to Rising Seas. Not Everyone Is Convinced.," *The New York Times*, March 2, 2021, sec. Climate, https://www.nytimes.com/2021/03/02/climate/miami-sea-level-rise.html.
136 "Tribal Nations," U.S. Climate Resilience Toolkit, September 19, 2023, https://toolkit.climate.gov/topics/tribal-nations.
137 "Natural Resources," Shinnecock Nation, accessed September 23, 2023, https://www.shinnecock-nsn.gov/environmental-natural-resources; John Linstrom, "Indigenous Sovereignty, Sea Level Rise, and the Shinnecock Nation," Climate Museum, November 17, 2022, https://climatemuseum.org/blog/2022/11/17/indigenous-sovereignty; "Sustainable Food Systems," Shinnecock Nation, accessed September 23, 2023, https://www.shinnecock-nsn.gov/environmental-sustainable-food.
138 Linstrom, "Indigenous Sovereignty, Sea Level Rise, and the Shinnecock Nation."

139 Anuradha Varanasi, "The Tribe That Brought a Damaged Shoreline Back to Life," *State of the Planet* (blog), September 18, 2019, https://news.climate.columbia.edu/2019/09/18/shinnecock-coastal-habitat-restoration-project/.
140 Reeder-Myers et al., "Indigenous Oyster Fisheries Persisted for Millennia and Should Inform Future Management."
141 Nick Bradford, "US Coral Reefs in a Warming Ocean," National Environmental Education Foundation, accessed September 23, 2023, https://www.neefusa.org/story/climate-change/us-coral-reefs-warming-ocean.
142 "Tribal Nations."
143 Toni Makani Gregg et al., "Puka Mai He Ko'a: The Significance of Corals in Hawaiian Culture," in *Ethnobiology of Corals and Coral Reefs*, ed. Nemer Narchi and Lisa Leimar Price, Ethnobiology (Springer, Cham, 2015), 103–15, https://doi.org/10.1007/978-3-319-23763-3_7.
144 "National Fish Habitat Partnership Projects to Engage Recreational Fishing Communities and Restore Habitat," NOAA Fisheries, June 2, 2023, Alaska, Pacific Islands, Southeast, National, https://www.fisheries.noaa.gov/feature-story/national-fish-habitat-partnership-projects-engage-recreational-fishing-communities-and.
145 "NOAA's 'Green' Expertise Meets New Infrastructure Era," Office for Coastal Management, accessed September 23, 2023, https://coast.noaa.gov/states/stories/green-meets-new.html.
146 "Biden-Harris Administration Announces $2.6 Billion Framework through Investing in America Agenda to Protect Coastal Communities and Restore Marine Resources," National Oceanic and Atmospheric Administration, June 6, 2023, https://www.noaa.gov/news-releases/noaa-ira-framework-2023.
147 "Biden-Harris Administration Announces More than $3 Billion in Funding for Two FEMA Programs to Increase Climate Resilience Nationwide," Federal Emergency Management Agency, August 12, 2022, https://www.fema.gov/press-release/20220812/biden-harris-administration-announces-more-3-billion-funding-two-fema; "Biden-Harris Administration Announces an Additional $160 Million to Build Climate and Disaster Resilience Nationwide, Including Over $50 Million for Tribal Nations," Federal Emergency Management Agency, May 19, 2023, https://www.fema.gov/press-release/20230519/biden-harris-administration-announces-additional-160-million-build-climate.
148 "Estimated Flood Loss Potential" (National Flood Insurance Program, July 29, 2019), https://www.floodsmart.gov/sites/default/files/flood-loss-potential_jul19.pdf.
149 Darryl Fears and Lori Rozsa, "The Price of Living near the Shore Is Already High. It's about to Go through the Roof.," *The Washington Post*, October 1, 2021, https://www.washingtonpost.com/climate-environment/2021/10/01/price-living-near-shore-is-already-high-its-about-go-through-roof/.
150 Union of Concerned Scientists. "Overwhelming Risk: Rethinking Flood Insurance in a World of Rising Seas." Union of Concerned Scientists, 2013, http://www.jstor.org/stable/resrep00031.
151 Diane P. Horn, "A Brief Introduction to the National Flood Insurance Program" (Congressional Research Service, January 4, 2023), https://sgp.fas.org/crs/homesec/IF10988.pdf.
152 Christopher Flavelle, "The Cost of Insuring Expensive Waterfront Homes Is About to Skyrocket," *The New York Times*, September 24, 2021, sec. Climate, https://www.nytimes.com/2021/09/24/climate/federal-flood-insurance-cost.html.
153 Michael Allen, "Protection for the Rich, Retreat for the Poor," Hakai Magazine, October 14, 2020, https://hakaimagazine.com/news/protection-for-the-rich-retreat-for-the-poor/.
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.
156 "Sea Level Rise Viewer," National Oceanic and Atmospheric Administration, accessed June 13, 2023, https://coast.noaa.gov/slr/#/layer/sce/0/-8648349.632688306/4263400.437507084/6/satellite/47/1/2050/interHigh/midAccretion.
157 Douglas L. Inman and Robert Dolan, "The Outer Banks of North Carolina: Budget of Sediment and Inlet Dynamics along a Migrating Barrier System," *Journal of Coastal Research* 5, no. 2 (1989): 193–237; "North Carolina," Coastal Resilience, accessed June 13, 2023, https://coastalresilience.org/project/north-carolina/.
158 David Mallison et al., "Barrier Island and Estuary Co-evolution in Response to Holocene Climate and Sea-Level Change: Pamlico Sound and the Outer Banks Barrier Islands, North Carolina, USA," in *Barrier Dynamics and Responses to Changing Climate* (Springer, Cham, January 2018): 91-120, https://doi.org/10.1007/978-3-319-68086-6_3.

159 Michael Barber, "Group of Three National Park Sites in Eastern North Carolina Hosted Record Number of Visits in 2021," National Park Service, February 10, 2022, https://www.nps.gov/caha/learn/news/group-of-eastern-north-carolina-national-park-sites-host-record-visits-in-2021.htm.
160 Sam Walker, "Visitor spending increases in all 100 counties in 2021, Dare fourth highest total in N.C.," *Island Free Press*, August 19, 2022, https://islandfreepress.org/outer-banks-news/visitor-spending-increases-in-all-100-counties-in-2021-dare-third-highest-total-in-n-c/.
161 "Flood Risk Overview: Does Dare County Have Flood Risk?," Risk Factor, accessed June 14, 2023, https://riskfactor.com.
162 "Sea Level Rise Viewer."
163 "Dare County, North Carolina, 2022," U.S. Census Bureau QuickFacts, accessed June 13, 2023, https://www.census.gov/quickfacts/fact/table/darecountynorthcarolina/PST045222; "7 Things to Know Before Visiting the Outer Banks," Outer Banks Concierge, accessed June 15, 2023, https://www.outerbanksconcierge.com/blog/post/7-things-to-know-before-visiting-the-outer-banks-5/; Brady Dennis, "Retreat in Rodanthe," *Washington Post*, March 13, 2023, https://www.washingtonpost.com/climate-environment/interactive/2023/obx-rodanthe-erosion-rising-sea-levels/.
164 Rachel M. Gregg and Kathryn Braddock, "Alligator River National Wildlife Refuge/Albemarle-Pamlico Peninsula Climate Adaptation Project," Climate Adaptation Knowledge Exchange, March 8, 2010, https://www.cakex.org/case-studies/alligator-river-national-wildlife-refugealbemarle-pamlico-peninsula-climate-adaptation-project.
165 Dennis, "Retreat in Rodanthe."
166 Catherine Kozak, "Myriad problems led to Rodanthe's doomed beach houses," *Island Free Press*, December 2, 2022, https://islandfreepress.org/outer-banks-news/myriad-problems-led-to-rodanthes-doomed-beach-houses/.
167 Ibid.
168 "Saving an Icon: Moving the Cape Hatteras Lighthouse Away from the Shifting Shoreline," Union of Concerned Scientists, July 19, 2016, https://www.ucsusa.org/resources/moving-cape-hatteras-lighthouse-away-shifting-shoreline.
169 Gilbert M. Gaul, "Shifting Sands: Carolina's Outer Banks Face a Precarious Future," Yale Environment 360, July 14, 2022, https://e360.yale.edu/features/outer-banks-climate-change-flooding.
170 Irene Nolan, "Walking on Isabel Inlet and other tales of recovery," *Island Free Press*, August 1, 2013, https://islandfreepress.org/outer-banks-news/08012013-walkingonisabelinletandothertalesofrecovery/.
171 Keenan Willard, "'It's Reaching a Crisis Point': Outer Banks Leaders Say They're out of Funding to Save Threatened Beach Communities," *WRAL News*, January 20, 2023, https://www.wral.com/story/it-s-reaching-a-crisis-point-outer-banks-leaders-say-they-re-out-of-funding-to-save-threatened-beach-communities/20681815/.
172 Joy Crist, "With Rodanthe homes in danger of collapsing, NPS and county representatives provide updates on an imminent issue," *Island Free Press*, March 4, 2022, https://islandfreepress.org/outer-banks-news/with-rodanthe-homes-in-danger-of-collapsing-nps-and-county-representatives-provide-updates-on-an-imminent-issue/.
173 "Completed Beach Nourishment Projects," Dare County, North Carolina, accessed June 13, 2023, https://www.darenc.gov/government/beach-nourishment/completed-projects.
174 "Summary Report: Rodanthe Sand Needs Assessment" (Columbia, SC: Coastal Science & Engineering, May 2023), https://interactive.13newsnow.com/pdfs/Rodanthe-Sand-Needs-Assessment.pdf.
175 "N.C. Rodanthe Bridge," North Carolina Department of Transportation, accessed June 14, 2023, https://www.ncdot.gov/projects/nc-12-rodanthe/Pages/default.aspx.
176 Gittman et al., "Marshes with and without sills protect estuarine shorelines from erosion better than bulkheads during a Category 1 hurricane."
177 Ibid.
178 "Keep Estuarine Shorelines Healthy & Productive," North Carolina Coastal Federation, accessed June 14, 2023, https://www.google.com/maps/d/viewer?mid=1aMzg7YAfUbEpBJSSps0Y9kx9SyhQLK5W.
179 "Regional Plan Aims to Protect Salt Marsh as Sea Levels Rise," *Coastal Review*, May 18, 2023, https://coastalreview.org/2023/05/regional-plan-aims-to-protect-salt-marsh-as-sea-levels-rise/.
180 "SASMI Plan," South Atlantic Salt Marsh Initiative, accessed June 14, 2023, https://marshforward.org/.
181 Gregg and Braddock, "Alligator River National Wildlife Refuge/Albemarle-Pamlico Peninsula Climate Adaptation Project."

182 Lindsay Dubbs, "Living Shorelines: Benefits & Limitations" (Wanchese, NC, February 20, 2019), https://www.deq.nc.gov/coastal-management/coastal-reserve/coastal-training-program/past-workshops/lindsay-dubbs-living-shorelines-workshop-20feb19/download; Steve Hanf, "Restaurant To Reef; Oyster Recycling," *Outer Banks Coastal Life* (blog), November 24, 2020, https://outerbankscoastallife.com/oyster-shell-recycling/.
183 "Miami-Dade County, Florida, USA," Surging Seas Risk Finder, accessed September 23, 2023, https://riskfinder.climatecentral.org/county/miami-dade-county.fl.us.
184 Flavelle and Mazzei, "Miami Says It Can Adapt to Rising Seas. Not Everyone Is Convinced."
185 Shimon Wdowinski et al., "Increasing Flooding Hazard in Coastal Communities Due to Rising Sea Level: Case Study of Miami Beach, Florida," *Ocean & Coastal Management* 126 (June 1, 2016): 1–8, https://doi.org/10.1016/j.ocecoaman.2016.03.002.
186 "Water Supply and Treatment," Miami-Dade County, accessed October 17, 2023, https://www.miamidade.gov/global/water/water-supply-and-treatment.page; Pamela Cabrera, "The Vulnerability of Potable Water with Climate Change in Miami-Dade," Harvard Graduate School of Design, Spring 2018, https://www.gsd.harvard.edu/project/the-vulnerability-of-potable-water-with-climate-change-in-miami-dade/.
187 "Flood Risk Overview: Does Miami-Dade County Have Flood Risk?," Risk Factor, accessed October 17, 2023, https://riskfactor.com/county/miami-dade-county-florida/12086_fsid/flood#current_&_future_risk.
188 Marilyn C. Montgomery and Jayajit Chakraborty, "Assessing the Environmental Justice Consequences of Flood Risk: A Case Study in Miami, Florida," *Environmental Research Letters* 10, no. 9 (2015): 095010.
189 Patricia Sagastume, "Researchers Aim to Resolve Inequity in Miami's Flood Preparation," *Al Jazeera*, March 5, 2014, http://america.aljazeera.com/articles/2014/3/5/researchers-aim-toresolveinequityinmiamisfloodprep.html.
190 "Flood Risk Overview: Does Miami-Dade County Have Flood Risk?"
191 "Sea Level Rise and Flooding," Miami-Dade County, accessed September 24, 2023, https://www.miamidade.gov/global/economy/resilience/sea-level-rise-flooding.page.
192 "Sea Level Rise and Flooding."
193 "Sea Level Rise Strategy," Miami-Dade County, accessed September 23, 2023, https://www.miamidade.gov/global/economy/resilience/sea-level-rise-strategy.page.
194 "Miami-Dade County Sea Level Rise Strategy" (Miami-Dade County, February 2021), https://miami-dade-county-sea-level-rise-strategy-draft-mdc.hub.arcgis.com/.
195 "Miami-Dade County Sea Level Rise Strategy: Executive Summary" (Miami-Dade County, February 2021), https://miami-dade-county-sea-level-rise-strategy-draft-mdc.hub.arcgis.com/.
196 "Miami-Dade County Sea Level Rise Strategy: Year 1 Progress" (Miami-Dade County, February 2022), https://miami-dade-county-sea-level-rise-strategy-draft-mdc.hub.arcgis.com/.
197 "About the Salish Sea," Salish Sea Institute, accessed September 23, 2023, https://salishsea.wwu.edu/about-salish-sea; "Salish Sea Rivers & Surface Currents," Western Washington University, accessed September 23, 2023, https://wp.wwu.edu/salishseaatlas/2023/06/14/salish-sea-rivers-surface-currents/.
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.
199 NOAA Fisheries, "Protecting the Critical Value of Nearshore Habitat," NOAA Fisheries, November 10, 2020, West Coast, https://www.fisheries.noaa.gov/feature-story/protecting-critical-value-nearshore-habitat; Kathryn L. Sobocinski, "Urbanization and Human Impacts to the Seascape" (Bellingham, WA: Western Washington University, May 2021
200 Clifford Mass and Brigid Dotson, "Major Extratropical Cyclones of the Northwest United States: Historical Review, Climatology, and Synoptic Environment," *Monthly Weather Review* 138, no. 7 (July 1, 2010): 2499–2527, https://doi.org/10.1175/2010MWR3213.1.
201 "Climate Change Indicators: Snowfall," Reports and Assessments, United States Environmental Protection Agency, July 21, 2023, https://www.epa.gov/climate-indicators/climate-change-indicators-snowfall; Kate Companion, "Trends Show Decreasing Snowfall in the Pacific Northwest, Potential Impacts to Water Supply," *The Daily of the University of Washington*, February 14, 2022, https://www.dailyuw.com/news/discoveries/trends-show-decreasing-snowfall-in-the-pacific-northwest-potential-impacts-to-water-supply/article_290569fc-8d68-11ec-99b9-3f44812001b2.html.
202 Ian Miller et al., "Projected Sea Level Rise for Washington State" (Washington Sea Grant, University of Washington Climate Impacts Group, University of Oregon, University of Washington, and US Geological Survey, 2018), https://cig.uw.edu/wp-content/uploads/sites/2/2019/07/SLR-Report-Miller-et-al-2018-updated-07_2019.pdf.

203 "Sea Level Rise Could Make Rivers More Likely to Jump Course," National Science Foundation, August 17, 2020, https://new.nsf.gov/news/sea-level-rise-could-make-rivers-more-likely-jump; Harriet A. Morgan et al., "State of Knowledge: Climate Change in Puget Sound" (Seattle, WA: Climate Impacts Group University of Washington, November 2015), https://data.cig.uw.edu/picea/mauger/ps-sok/PS-SoK_2015.pdf.

204 A. D Jayakaran et al., "Green Infrastructure in Western Washington and Oregon: Perspectives from a Regional Summit," *Urban Forestry & Urban Greening* 50 (April 1, 2020): 126654, https://doi.org/10.1016/j.ufug.2020.126654.

205 Emily Howe, "Stormwater Effluent Exerts a Key Pressure on the Salish Sea," State of the Salish Sea (Bellingham, WA: Salish Sea Institute, Western Washington University, 2021), https://cedar.wwu.edu/cgi/viewcontent.cgi?article=1008&context=salish_pubs.

206 "Toxics in the Food Web," Reports and Assessments, United States Environmental Protection Agency, March 10, 2023, Canada, Puget Sound, https://www.epa.gov/salish-sea/toxics-food-web.

207 Darryl Fears, "As Salmon Vanish in the Dry Pacific Northwest, so Does Native Heritage," *Washington Post*, July 30, 2015, https://www.washingtonpost.com/national/health-science/as-salmon-vanish-in-the-dry-pacific-northwest-so-does-native-heritage/2015/07/30/2ae9f7a6-2f14-11e5-8f36-18d1d501920d_story.html.

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

209 Ibid.

210 Jim Johannessen and Avery Maverick, "Residential Shoreline Loan Program Feasibility Study Cost Analysis Memo" (Bellingham: Coastal Geologic Services, 2020), https://www.eopugetsound.org/sites/default/files/features/resources/Appendix_3-CostAnalysisMemo.pdf.

211 "Washington Coastal Resilience Project," Climate Impacts Group, accessed September 24, 2023, https://cig.uw.edu/projects/washington-coastal-resilience-project/.

212 "Smith Island Restoration Project," Snohomish County, accessed September 24, 2023, https://snohomishcountywa.gov/1150/Smith-Island-Restoration-Project.

213 Paul M. Bayle et al., "Behaviour and Performance of a Dynamic Cobble Berm Revetment during a Spring Tidal Cycle in North Cove, Washington State, USA," *Coastal Engineering* 167 (August 1, 2021): 103898

214 "Biden-Harris Administration Recommends Funding of $74.4 Million for Projects in Washington State to Strengthen Climate-Ready Coasts as Part of Investing in America Agenda," National Oceanic and Atmospheric Administration, April 21, 2023, https://www.noaa.gov/news-release/noaa-bil-investments-2023-washington-state; "Chinook Salmon," Reports and Assessments, United States Environmental Protection Agency, Canada, Puget Sound, accessed September 23, 2023, https://www.epa.gov/salish-sea/chinook-salmon.

215 White House Council on Environmental Quality, White House Office of Science and Technology Policy, and White House Domestic Climate Policy Office, "Opportunities to Accelerate Nature-Based Solutions: A Roadmap for Climate Progress, Thriving Nature, Equity, & Prosperity" (Washington, D.C.: The White House, November 2022), https://www.whitehouse.gov/wp-content/uploads/2022/11/Nature-Based-Solutions-Roadmap.pdf.

216 Ibid.

217 "Risk Rating 2.0: Equity in Action," Federal Emergency Management Agency, September 1, 2023, https://www.fema.gov/flood-insurance/risk-rating

218 "FACT SHEET: Biden-Harris Administration Announces Roadmap for Nature-Based Solutions to Fight Climate Change, Strengthen Communities, and Support Local Economies," The White House, November 8, 2022, https://www.whitehouse.gov/briefing-room/statements-releases/2022/11/08/fact-sheet-biden-harris-administration-announces-roadmap-for-nature-based-solutions-to-fight-climate-change-strengthen-communities-and-support-local-economies/.

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.

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