Living Shorelines and Coastal Resilience: A Systematic Review of Effectiveness

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Master of Science in Integrated Science and Technology
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Any assistance received in the completion of this project, including the use of generative Artificial Intelligence (AI) tools such as ChatGPT, has been transparently acknowledged in the attached acknowledgment form.

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During the preparation of this work, the author used Consensus in order to search for relevant papers. Grammarly and ChatGPT were additionally used to facilitate brainstorming and improve the readability and language of the work. AI tools were not used to generate content that constitutes the main intellectual contribution of the capstone.

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I would like to express my deepest gratitude to all those who supported me throughout the process of completing this capstone project, and a special thank you to my supervisors for their invaluable guidance and input.

Abstract

This capstone presents a systematic review of peer-reviewed literature that evaluates the effectiveness of living shorelines as a nature-based solution for enhancing coastal resilience. Drawing on 33 studies published between 2008 and 2025, the review synthesizes evidence across four primary domains: erosion control, biodiversity and habitat support, water quality and ecosystem services, and socio-economic benefits. Findings indicate that living shorelines consistently reduce shoreline erosion, particularly in high-energy environments, when hybrid designs incorporating structural elements are employed. Biodiversity outcomes were generally positive, with restored sites supporting nekton communities, submerged aquatic vegetation, and intertidal invertebrates that were comparable to or exceeded natural reference conditions. Living shorelines also contributed to improved water quality through enhanced nutrient cycling, sediment retention, and carbon storage, particularly in marsh-based and oyster-integrated systems.

Additionally, evidence suggests living shorelines provide economic co-benefits by protecting property, supporting recreation and tourism, and offering long-term cost savings. However, variability in site conditions, design approaches, and monitoring practices limits generalizability and highlights the need for standardized metrics and long-term evaluations. This review supports the growing body of evidence that living shorelines are a multifunctional tool for climate adaptation and sustainable coastal management while also identifying research and policy gaps that must be addressed to optimize future implementation.

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1 Introduction

1.1 Contextualizing the problem

Coastal erosion is the process by which wind, waves, and longshore currents transport sediment away from the shoreline and deposit it elsewhere, such as in other coastal areas, the deep ocean floor, or ocean trenches (Pang et al., 2023). The loss of sediment from the natural sediment-sharing system results in lasting alterations to the coastline's form and structure (Pang et al., 2023). Coastal erosion is a major global issue that threatens shorelines, and its effects are becoming more severe due to rising sea levels, the impacts of climate change, and human activities such as coastal development and resource extraction. As climate change intensifies, so does the rate at which coastal environments erode, threatening ecosystems, infrastructure, and coastal communities. Globally, approximately 24% of sandy beaches are experiencing erosion, with 7% undergoing severe erosion, characterized by rates of erosion of -5 to -3 m/yr (Luijendijk et al., 2018). In the United States, beaches in South Carolina, Virginia, Louisiana, and Texas have experienced more than two meters of shoreline erosion per year over the last century (U.S. Geological Survey, 2022). While coasts in North Africa face similar issues, nations such as Morocco and Egypt are experiencing coastal erosion that surpasses the global average by a factor of ten (Global Center on Adaptation, 2022). These trends are exacerbated by the disruption of natural sediment flows due to river damming, shoreline armoring, and other infrastructural interventions that limit sediment replenishment. Global coastal erosion has profound ecological and socio-economic implications, including the degradation of critical habitats, loss of biodiversity, and increased vulnerability of coastal populations, particularly in developing nations, to displacement, economic instability, and rising adaptation costs.

Traditional hard shoreline structures such as seawalls, bulkheads, and revetments have long been used to combat erosion but often produce unintended consequences, including habitat loss, increased erosion downstream, and reduced water quality. In response to these challenges, living shorelines have emerged as a promising alternative that combines ecological restoration with shoreline stabilization. Defined by agencies like NOAA as coastal edges protected and stabilized using natural materials such as native plants, sand, and oyster reefs, living shorelines aim to reduce erosion while enhancing habitat connectivity, biodiversity, and water quality (Figure 1).

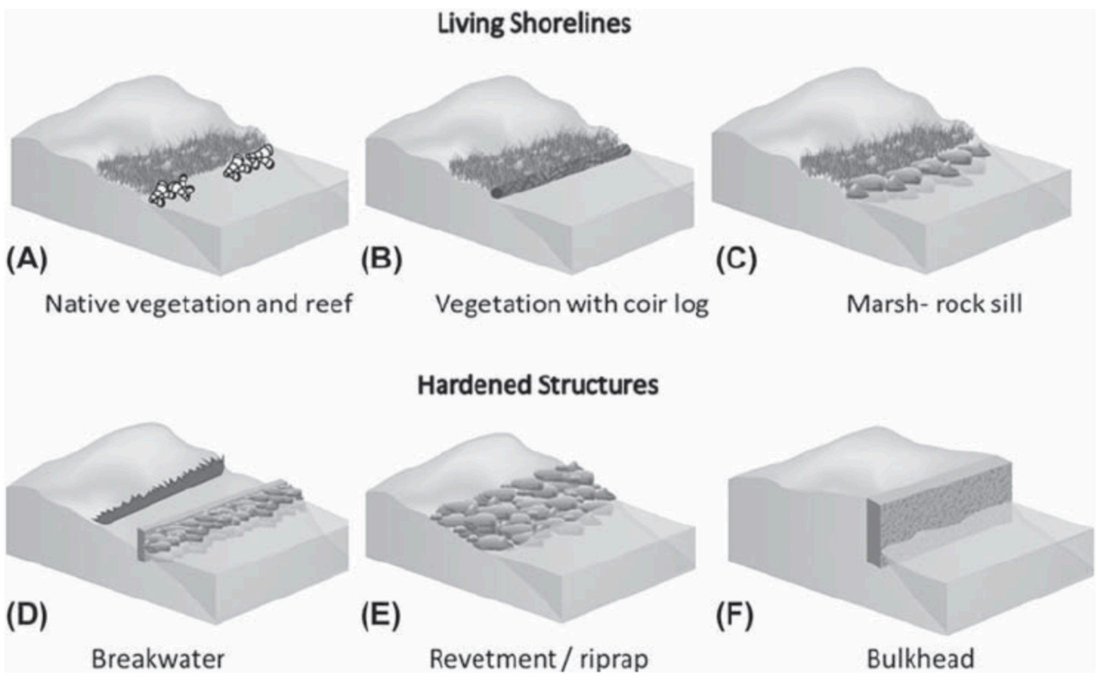

Figure 1: Shoreline Stabilization Approaches: Living Shorelines vs. Hardened Structures
Illustrations of shoreline stabilization approaches ranging from nature-based solutions to engineered structures. Panels A–C depict various types of living shorelines, including (A) native marsh vegetation and reef, (B) native vegetation with a coir log at the marsh toe, and (C) native marsh paired with an offshore rock sill. Panels D–F show hardened structures, such as (D) offshore stone breakwater, (E) stone revetment or riprap, and (F) vertical bulkhead. This visual comparison highlights the ecological gradients and engineering intensities used in shoreline protection. *Image adapted from* Currin, C. A. *(2019). Living Shorelines for Coastal Resilience*. SAGE. Retrieved from https://www.sagesagecoast.org/docs/Living%20Shoreline%20Brochure_Inside.jpg

Importantly, living shorelines also provide critical habitat for fish, birds, and invertebrates, support water filtration, and increase the potential for carbon sequestration, contributing to both climate mitigation and adaptation goals (Bilkovic et al., 2016). In doing so, they address the ecological degradation associated with hard-armoring methods, which often sever land-sea connections and accelerate erosion in adjacent areas (Scyphers et al., 2011). Moreover, living shorelines contribute to community resilience by reducing flood risk, enhancing recreational value, and buffering infrastructure from storm surges, which is especially vital as the frequency and intensity of extreme weather events continue to rise due to climate change (Arkema et al., 2013).

The decision to study living shorelines as a solution arises from their increasing adoption as a sustainable coastal management practice and the recognized need for a better understanding of their effectiveness across diverse environmental settings. Despite widespread interest, existing research reveals significant variability in the outcomes of living shoreline projects, partly due to differing site conditions, design approaches, and evaluation metrics. This inconsistency presents challenges for coastal planners and policymakers seeking to scale and optimize the implementation of living shorelines.

This capstone employs a literature review to explore and address these knowledge gaps. A systematic review of peer-reviewed literature was conducted to synthesize findings on the performance of living shorelines, focusing on erosion control, ecological benefits, and socio-economic impacts.

The research findings underscore the importance of site-specific design tailored to local hydrodynamics and habitat conditions. Results indicate that living shorelines can provide erosion control comparable to, or even exceeding, that of hard structures while also delivering superior ecological benefits, such as habitat creation and water filtration. However, the lack of standardized evaluation criteria and long-term monitoring remains a critical obstacle to fully understanding their performance and informing best practices. These insights highlight the need for coordinated efforts to develop consistent metrics and expand adaptive management frameworks.

By advancing the understanding of living shorelines' role in coastal resilience, this capstone contributes to the ongoing shift toward nature-based solutions that harmonize infrastructure needs with ecosystem health. The study's recommendations aim to guide future research, policy development, and practical implementation, fostering sustainable and resilient coastal communities.

1.2 Background Literature Review

The following literature review provides context for understanding the increasing environmental pressures on coastal zones, particularly concerning shoreline erosion and the emerging role of living shorelines as a nature-based adaptation strategy. This section begins by examining patterns of coastal population growth and associated environmental impacts, then explores the evolution of shoreline stabilization methods, concluding with a focus on the effectiveness and challenges of living shorelines, as documented in recent studies.

1.2.1 Coastal Population Growth and Environmental Pressures

Attracted by the beauty of picturesque coastlines, coastal communities have experienced rapid population growth and urban development, which has stressed fragile shoreline ecosystems. As a result, coastal ecosystems have begun to experience the phenomenon known as “coastal squeeze,” characterized by the loss or deterioration of natural habitats due to anthropogenic activities and encroachments that impact their ability to shift their range landward in response to sea level rise (Burden et al., 2020). Globally, more than half of the world’s population lives within the near-coastal zone, characterized as land within 100 kilometers of the coast, and of that, nearly 900 million people live below sea level, further increasing their vulnerability to coastal hazards such as storm surge, flooding, and erosion (Reimann et al., 2023) (Figure 2). For example, in the United States, 51% of the population

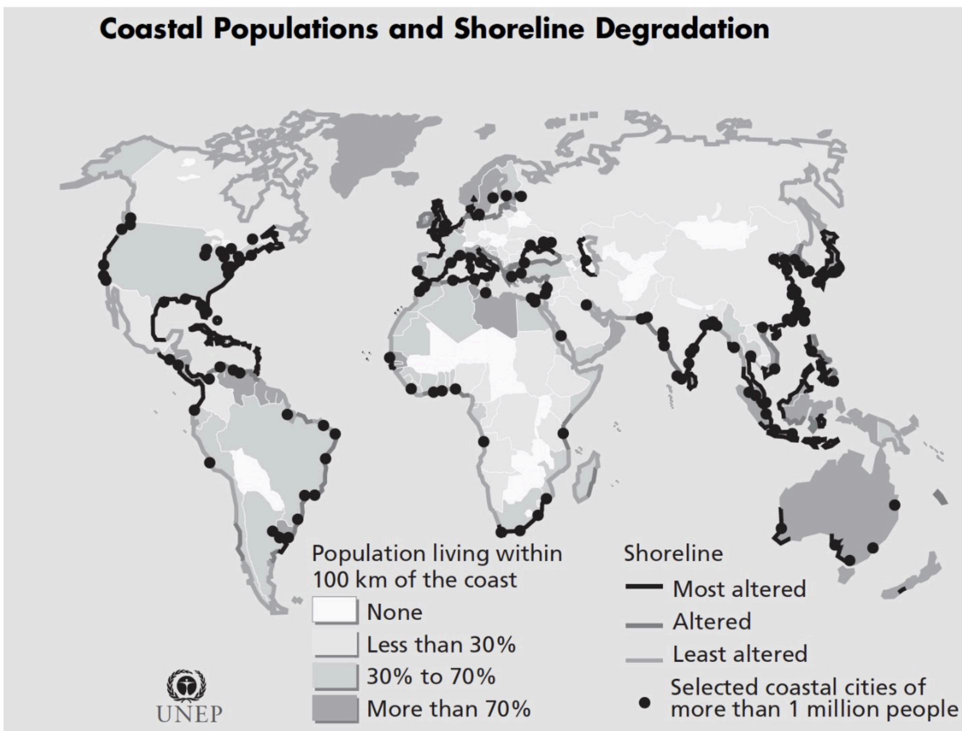

Figure 2: Coastal Populations and Shoreline Degradation
Illustration of global patterns of coastal population density and shoreline alteration. Countries are shaded to indicate the percentage of their population living within 100 kilometers of the coast. The map highlights the high concentration of urban centers along heavily altered coastlines, particularly in Southeast Asia, Western Europe, and the eastern coasts of North and South America.
Sources: United Nations Environment Programme. (2001). [Map of coastal ecosystems]. In L. Burke et al., Pilot analysis of global ecosystems: Coastal ecosystems. World Resources Institute.t

resides in coastal counties, which account for only 13% of the total land area (Erdle et al., 2006). Similarly, in the European Union, more than 40% of the population lives within 50 kilometers of a coastline (European Space Agency, 2021). This concentration of human activity intensifies demand for housing, transportation, industry, and recreational infrastructure, often leading to habitat loss, increased pollution, and altered natural processes. The near-coastal zone includes 66 large marine ecosystems (LMEs) that transcend geopolitical borders and serve as critical ecological and economic zones (World Ocean Review, 2013) (Figure 3). These LMEs are defined by ecological criteria, from bathymetry, hydrography, productivity, and tropically dependent populations (Kelley & Sherman, 2018). LMEs support diverse biological communities, including commercially important fisheries, and provide essential ecosystem services such as carbon sequestration, nutrient cycling, and coastal protection (Henshaw, 2017). However, the transboundary nature of large marine ecosystems poses a challenge for coordinated governance and environmental management. Figure 2 highlights the geopolitical complexity of LME management, as many span multiple national jurisdictions, underscoring the need for coordinated international governance and ecosystem-based management approaches. The intense anthropogenic activity concentrated in these zones has placed extreme pressure on marine resources, exacerbating coastal degradation. Increased development on coastlines to support growing populations has led to the degradation and loss of coastal ecosystems, impacting their resilience to extreme weather events and subsequent growth. As populations in these transboundary coastal zones continue to grow, the lack of unified regulatory frameworks complicates efforts to address erosion, pollution, and habitat loss, underscoring the need for collaborative, ecosystem-based management strategies.

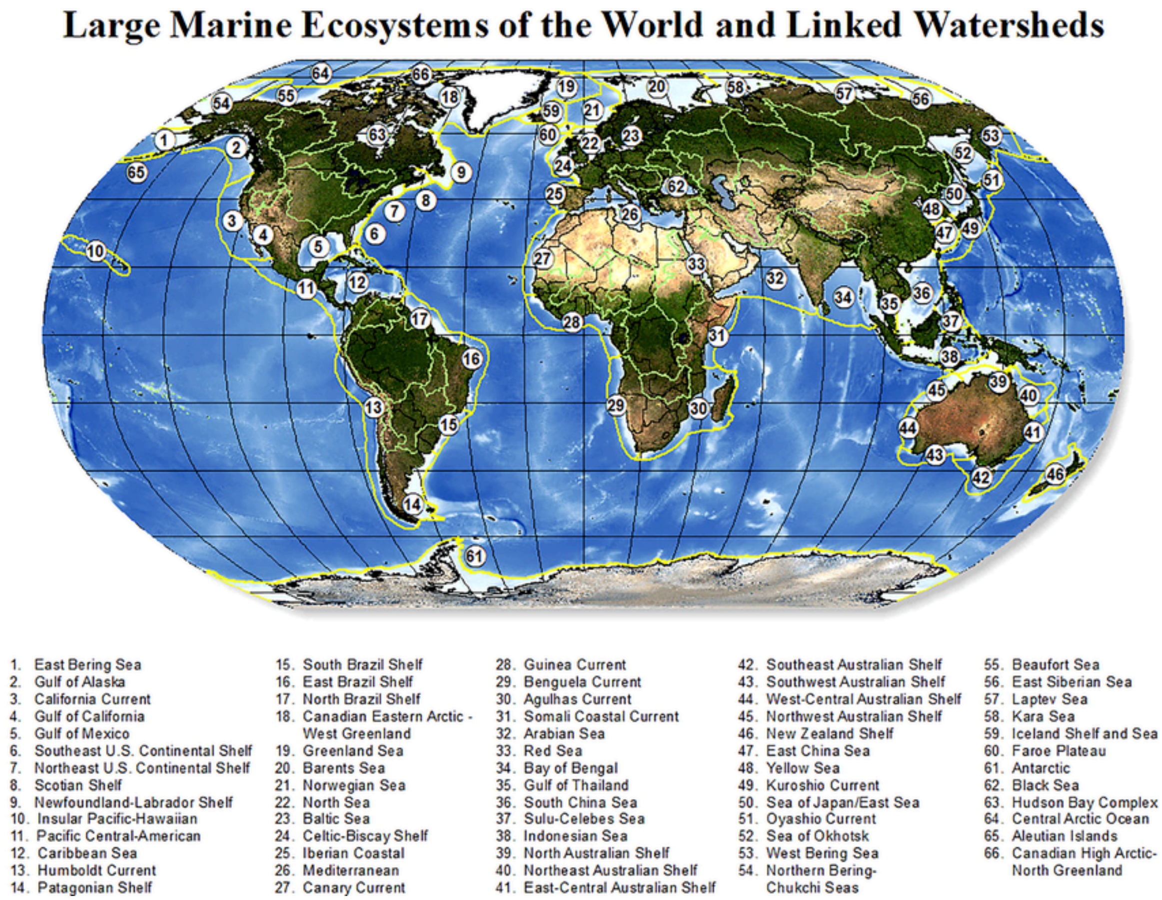

Figure 3. Map of the world's 66 Large Marine Ecosystems (LMEs)
This map illustrates the transboundary nature and global distribution of large marine ecosystems. LMEs are defined by ecological criteria such as bathymetry, productivity, and species composition and are critical for supporting marine biodiversity, fisheries, and coastal livelihoods.
Source: Chen, Dongxing & Wang, Xutao & Hou, Minchi & Wang, Qiabin & Liu, Qianqian & Huang, He & Zhang, Yafeng. (2022). Carbon Transfer Efficiency and Risk of Fisheries Collapse in Three Large Marine Ecosystems Around China. Frontiers in Marine Science. 9. 10.3389/fmars 2022.863611.

1.2.2 The Rise and Consequences of Hardened Shoreline Structures

When coastal erosion was first recognized as a serious and emerging problem, hard shoreline structures were widely used as the primary method of defense. These structures, including groins, jetties, seawalls, revetments, and breakwaters, were designed to protect shorelines by deflecting wave energy and stabilizing the coast (National Park Service, 2019) (Figure 1).

Initially, these structures were seen as effective, particularly in high-energy environments where immediate erosion control was prioritized.
However, while these anthropogenic fortifications provided short-term protection in specific areas, they often worsened erosion in adjacent or downstream locations and intensified the loss of biodiversity along shorelines (McClenachan et al., 2020; Polk & Eulie, 2018). By interrupting natural sediment transport, hard structures frequently create a cycle of erosion that requires the construction of additional barriers to protect newly exposed areas (National Park Service, 2019). In addition to these physical impacts, hard infrastructure typically replaces natural habitats such as tidal wetlands, marshes, and shallow subtidal zones, reducing habitat complexity and leading to significant losses in shoreline biodiversity. Studies have shown that armored shorelines provide poor habitat for many estuarine and marine species, especially compared to vegetated or natural shorelines, which support key ecosystem functions such as nutrient cycling, filtration, and fish nursery grounds (Bilkovic et al., 2016). The widespread use of hard stabilization has, therefore, not only reshaped coastal geomorphology but has also contributed to long-term ecological degradation.

As the ecological and physical shortcomings of hard shoreline armoring have become increasingly evident, policymakers and environmental agencies have begun to re-evaluate traditional coastal management techniques, prompting calls for more holistic, adaptive, and sustainable shoreline protection strategies. In response, state and federal agencies in the United States have initiated reforms to promote the adoption of living shorelines and other nature-based alternatives.

The most notable policy shifts occurred in Maryland, where the Living Shorelines Protection Act of 2008 mandated that living shorelines become the preferred method of shoreline stabilization in tidal wetlands (The Pew Charitable Trusts, 2019). This legislation required landowners to adequately demonstrate that hard armoring is necessary if selected instead (The Pew Charitable Trusts, 2019). The legislation marked a significant shift away from shoreline armoring norms to an increased reliance on integrated ecosystem management. Similarly, Virginia and North Carolina have implemented living shoreline guidance and permitting processes that streamline approval for softer, ecologically beneficial approaches while increasing scrutiny on new hard infrastructure (Allen, 2019; Wetland Studies and Solutions, Inc., 2022).

At the federal level, the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Army Corps of Engineers (USACE), along with other agencies, have supported the transition toward living shorelines through funding, technical guidance, and demonstrations (NOAA, 2015; Miller et al., 2015). A few European countries have also joined the effort to promote the broader adoption of living shorelines through their "building with nature" initiatives, including those in the United Kingdom, Belgium, the Netherlands, and France. The "building with nature" initiative advocates for the implementation of nature-based solutions to mitigate flood risk, primarily guided by national and European Union legislation (Bilkovic, 2017).

Recognizing the limitations and unintended consequences of hard structures, coastal managers and scientists began exploring alternative approaches that offer both shoreline protection and ecological benefits. These policy shifts have not only catalyzed the growth of living shoreline implementation but also laid the groundwork for future research, innovation, and broader adoption in response to growing coastal challenges.

1.2.3 Emergence of Living Shorelines as Nature-Based Solutions

To counteract the negative impacts of hard shoreline armoring, nature-based approaches commonly referred to as “living shorelines,” “green,” or “soft” shorelines, were constructed along shorelines in the 1970s (National Oceanic and Atmospheric Administration Fisheries, n.d.; Restore America’s Estuaries, 2015). NOAA defines living shorelines as “protected, stabilized coastal edges made of natural materials such as plants, sand, or rock” that evolve to enhance shoreline resilience and ecological diversity (National Oceanic and Atmospheric Administration Fisheries, n.d.). The modern living shoreline approach is widely credited to Dr. Edgar Garbisch Jr., who emerged as an early advocate for nature-based coastal stabilization in the mid-1970s (Poskaitis, 2021). While working in the Chesapeake Bay region, Dr. Garbisch conducted pioneering experiments using Spartina (native marsh grasses) and low-profile “marsh sills” to buffer wave energy and mitigate shoreline erosion. His findings demonstrated that these ecological interventions could not only stabilize shorelines effectively but also improve habitat quality for aquatic species, often outperforming traditional hard infrastructure such as seawalls and bulkheads.

1.2.4 Benefits and Challenges of Living Shoreline Implementation

While a universal framework for evaluating the long-term performance of living shorelines remains underdeveloped (Mednikova et al., 2023), a growing body of literature affirms their potential to deliver both physical protection and ecological value. Living shorelines are increasingly recognized for their ability to mitigate wave energy, reduce shoreline erosion, and address the "coastal squeeze" phenomenon.

Researchers at NOAA report that a single square mile of salt marsh has the potential to sequester around 76,000 gallons of greenhouse gases annually (National Oceanic and Atmospheric Administration Fisheries, n.d.). Additionally, for every 15 feet of living shorelines utilizing marshes and oyster reefs, around 50% of incoming wave energy is absorbed (National Oceanic and Atmospheric Administration Fisheries, n.d.). Polk and Eulie (2018) emphasize that living shorelines can enhance the provision of ecosystem services in coastal zones, thereby improving carbon storage, protecting against erosion, providing habitat, and facilitating water filtration.

In addition to the ecological benefits that living shorelines provide, they also offer significant economic benefits to the communities where they are installed. Following Hurricanes Irene (2011) and Arthur (2014), property owners reported that their repair costs for their bulkheads were almost double those of property owners with living shorelines, and bulkhead owners also paid four times as much for annual shoreline maintenance (Smith et al. 2017). Living shorelines also have significant implications for the success of fisheries, as the restored marshes and wetlands provide stable food sources for fish, drawing them into the area. In Virginia’s Middle Peninsula, the implementation of living shorelines has generated annual benefits of 6.4 million dollars from recreational fishing for the region (Wallace, 2024). A study conducted by William and Mary’s Virginia Institute of Marine Science (VIMS) reported that the Middle Peninsula's economic benefits are three and a half times greater than those of hardened shorelines (Wallace, 2024).

Despite the evident benefits of using living shorelines versus traditional hard armoring, several studies have identified practical and environmental limitations that constrain the feasibility of living shorelines. Multiple studies noted that high-energy wave environments are often too harsh for living shorelines to be installed without supportive armoring structures (Bilkovic, 2017; Currin, 2019). Another emerging criticism of living shoreline implementation centers on the use of hybrid approaches. These designs incorporate both natural elements and structural components in higher-energy or high-risk coastal environments. While these hybrid models are often necessary for structural stability, they introduce ambiguity in classification and evaluation. Projects that rely heavily on structural elements may be misidentified as living shorelines, even when they lack key ecological features such as vegetation or habitat enhancement (Bilkovic, 2017). This mislabeling can dilute the definition of living shorelines, hinder accurate performance comparisons, and contribute to confusion among regulators, practitioners, and the public regarding what truly constitutes a nature-based solution (Currin, 2019). The absence of clearly defined thresholds for what qualifies as a living shoreline further exacerbates this issue, underscoring the need for standardized criteria and typologies across environmental and regulatory contexts. For example, in Europe, coastal protection strategies often rely on engineered interventions, such as seawalls or managed realignment, the deliberate inland relocation of a coastal defense line to allow space for natural processes, like tidal marsh restoration (Bilkovic et al., 2017). While managed realignment shares some ecological goals with living shorelines, such as habitat creation and erosion control, it operates under a different regulatory and conceptual framework.

Steep bluffs, proximity to critical infrastructure, and nearby navigational channels can significantly reduce the effectiveness of living shorelines or render their installation unfeasible in certain locations (Currin, 2019). Additionally, factors such as local land-use patterns, shoreline morphology, and restrictive permitting processes further constrain where and how living shorelines can be deployed. These site-specific limitations often necessitate complex engineering adaptations to meet both ecological goals and structural requirements. Such modifications can increase project costs, extend permitting timelines, and ultimately hinder the scalability of living shoreline solutions. As a result, while living shorelines hold promise as sustainable alternatives to hard armoring, their practical implementation remains uneven and highly context dependent.

1.2.5 Gaps in Knowledge and Research Limitations

While living shorelines have garnered increased attention as a sustainable alternative to hard armoring, substantial gaps remain in the literature regarding their performance across diverse environmental conditions. In particular, there is limited understanding of how open ocean exposure, hydraulic intensity, and wave climate affect the long-term functionality and resilience of these nature-based systems (Marino et al., 2025; Moraes et al., 2022). This lack of clarity has given rise to divergent perspectives on both the effectiveness of living shorelines and the appropriate metrics for evaluating success across ecological contexts.

For instance, De Roo and Troch (2015) note that few studies have fully examined the impact of high-energy hydraulic environments on the structural and ecological performance of living shorelines. Many studies briefly address the topic, but specific metrics and analyses of impact are lacking. Their research highlights how knowledge gaps and inadequate site assessments have led to the inappropriate placement of living shorelines in confined waterways impacted by high wave energy, resulting in increased erosion after installation. These findings underscore the critical need for site-specific guidance, refined risk assessments, and better predictive models that account for energy regimes, sediment dynamics, and habitat compatibility.

Furthermore, much of the existing research has been conducted in low- to moderate-energy settings, such as protected estuarine environments, limiting its applicability to more dynamic coastal zones (Smith et al., 2020). As living shorelines begin to scale across different geographies, this knowledge limitation raises concerns about the generalizability and long-term sustainability of these approaches. Addressing these research gaps is crucial for developing robust design standards and regulatory frameworks that can inform the effective implementation of living shorelines under varying environmental pressures. Without targeted, multidisciplinary investigations into their performance under high-energy conditions, the full potential of living shorelines to serve as a resilient coastal defense strategy remains constrained.

Stakeholder interviews conducted along the U.S. Pacific Coast, representing biologists, engineers, policymakers, coastal managers, and others across government agencies, nonprofits, academia, and consulting firms, have identified key research and implementation needs that are critical to advancing the science and practice of living shorelines (Mednikova et al., 2023). According to Mednikova et al. (2023), closing knowledge gaps will require investments in several areas: supporting early-stage demonstration projects, expanding training for engineers to apply nature-based infrastructure techniques, and conducting long-term monitoring of ecological health and structural performance.

These priorities highlight that addressing knowledge gaps is as much about investing in systems of learning and governance as it is about refining physical design. Bridging these gaps will require sustained collaboration between researchers, practitioners, funders, and frontline communities to ensure that living shorelines are not only effective and ecologically sound but also equitable, scalable, and socially responsive.

As living shorelines gain popularity, more reports and multi-state conferences have begun to focus on the research gaps around living shorelines. On the U.S. East Coast, several living shoreline conferences are held to close these research gaps. These include the 2006 Living Shoreline Summit; the 2013 Mid-Atlantic Living Shoreline Summit; the 2015 report from the National Science and Technology Council's Coastal Green Infrastructure and Ecosystem Task Force; and the 2016 South Atlantic Living Shoreline Summit (Morris et al., 2019; Myszewski & Alber, 2016). These conferences have all reached the consensus that there is a need for more quantitative studies focused on living shorelines and techniques to improve success across variable conditions (Myszewski & Alber, 2016). They additionally called for comparative assessments between nature-based and traditional shore stabilization methods.

Furthermore, Myszewski and Alber (2016) identified numerous knowledge gaps related to living shorelines, including the need for more research on ecological impacts, species diversity across different shoreline types, and the performance of living shorelines in improving water quality and nutrient removal. They also highlighted the need for additional modeling and field observations to assess coastal risk reduction and quantify the effects of natural features on storm surge, wave energy, and sediment retention.

Although living shorelines present a promising and ecologically sound alternative to traditional shoreline armoring, their broader adoption is hindered by significant gaps in scientific understanding, technical design guidance, and standardized evaluation. Current research is disproportionately focused on low-energy environments, leaving critical questions unanswered about performance in dynamic or high-energy settings. Inadequate metrics, limited long-term monitoring, and inconsistent classification frameworks further complicate assessment and hinder confidence among practitioners and policymakers. Stakeholder insights and multi-state conferences have repeatedly emphasized the need to address these limitations through more targeted, interdisciplinary research, expanded education and training, and increased investment in modeling, field trials, and performance monitoring. Future work must also incorporate environmental justice and equity considerations, ensuring that low-income and marginalized communities, which often experience disproportionate coastal flooding and erosion, can equally benefit from the protective and ecological enhancements provided by living shorelines (Lienhard & Fairbairn, 2023). Without deliberate attention to procedural (fair decision-making) and distributive (fair distribution of benefits) justice, these nature-based solutions risk reinforcing existing inequalities. Bridging these research and practice gaps is essential not only for improving the efficacy of living shoreline projects but also for scaling them as viable, adaptive tools in global efforts to enhance coastal resilience.

1.2.6 Barriers to Widespread Adoption

Despite their ecological promise and resilience-building potential, living shorelines have not yet achieved widespread adoption, largely due to entrenched institutional, economic, and social barriers. One major obstacle is institutional inertia, the tendency among stakeholders to default to familiar, conventional engineering solutions, often due to limited awareness or understanding of nature-based alternatives (Restore America's Estuaries, 2015). This resistance to change is compounded by a lack of technical training and clear regulatory frameworks to support nontraditional shoreline stabilization approaches.

Additionally, fragmented decision-making at the site level often fails to account for broader ecosystem or watershed-scale benefits. In many cases, the financial burden before implementation falls solely on individual shoreline property owners, even though the ecological and flood mitigation benefits of living shorelines extend to entire communities (Restore America's Estuaries, 2015). This imbalance in cost-sharing discourages adoption and further entrenches reliance on hard infrastructure.

Moreover, Restore America's Estuaries (2015) has demonstrated that the absence of a unified advocacy network has hindered coordination across disciplines and jurisdictions, thereby reducing the political momentum necessary to advance comprehensive living shoreline policy and funding mechanisms. Without clear leadership or collaborative platforms to unify stakeholders, ranging from engineers and environmental groups to policymakers and landowners, progress remains piecemeal and localized.

The preceding literature review highlights a critical tension in coastal management: although living shorelines offer both ecological and adaptive advantages, their broader application is limited by scientific uncertainties, regulatory stagnation, and systemic disincentives. To address these challenges, this capstone undertakes a systematic review of living shoreline interventions, aiming to evaluate their effectiveness in mitigating coastal erosion and enhancing biodiversity across diverse global contexts. The research also seeks to identify and, where necessary, propose standardized criteria for assessing the success of living shorelines to inform more consistent, equitable, and evidence-based adoption.

2 Methodology

This study adhered to the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for the systematic review process employed in this research (Page et al., 2021).

2.1 Literature Search

A comprehensive search strategy was employed, utilizing a combination of keywords and Boolean operators. The Web of Science, Scopus, Consensus, and Google Scholar databases were systematically searched from April to June 2025 using the following search strings: ("living shoreline" OR "living shorelines" OR "nature-based solutions") AND ("effective" OR "effectiveness").

The search results were imported into Zotero to manage references and identify duplicate results. A single reviewer screened the titles and abstracts using the established eligibility criteria. After identifying potentially relevant studies through title and abstract screening, full-text versions were obtained and thoroughly assessed for eligibility. The PRISMA flow diagram below (Figure 4) illustrates the article selection process, accounting for the number of studies identified, screened, excluded, and included in the final synthesis.

2.2 Eligibility Criteria

The literature search included peer-reviewed studies, engineering guidelines, and policy reports that examined the effectiveness of living shorelines in mitigating coastal erosion and enhancing biodiversity. For a study to be included, it had to be an empirical research study conducted in marine, estuarine, or brackish environments, explicitly identify "living shorelines" in its evaluation, be published between 2000 and 2025, and be written in English. Studies were excluded if they neglected to mention green infrastructure (natural marshes, living shorelines), focused primarily on gray infrastructure (seawalls, bulkheads), were characterized as review articles, conceptual papers, editorials, or did not clearly describe outcomes and methodologies relevant to shoreline protection or ecological improvements.

2.3 Data Collection

Data was extracted and logged in a managed Excel sheet to ensure standardization. The same data were extracted from all the reviewed studies to maintain consistency and uniformity across the studies. The extracted data included:

- Study location and year
- Type and scale of living shoreline
- Construction materials used (marsh grasses, oyster sill, coir logs)

- Physical outcomes (sediment accretion, wave attenuation, erosion rates)
- Ecological outcomes (species abundance, habitat creation, biodiversity)
- Study design and duration
- Key findings and limitations/gaps

A total of 100 records were identified through database searches. After removing duplicates, 81 records remained. The titles and abstracts were screened regarding the predetermined inclusion criteria, and all 81 were selected for full-text review. Of the total records identified and reviewed, 48 papers were excluded, and 33 met the full inclusion criteria after the final evaluation.

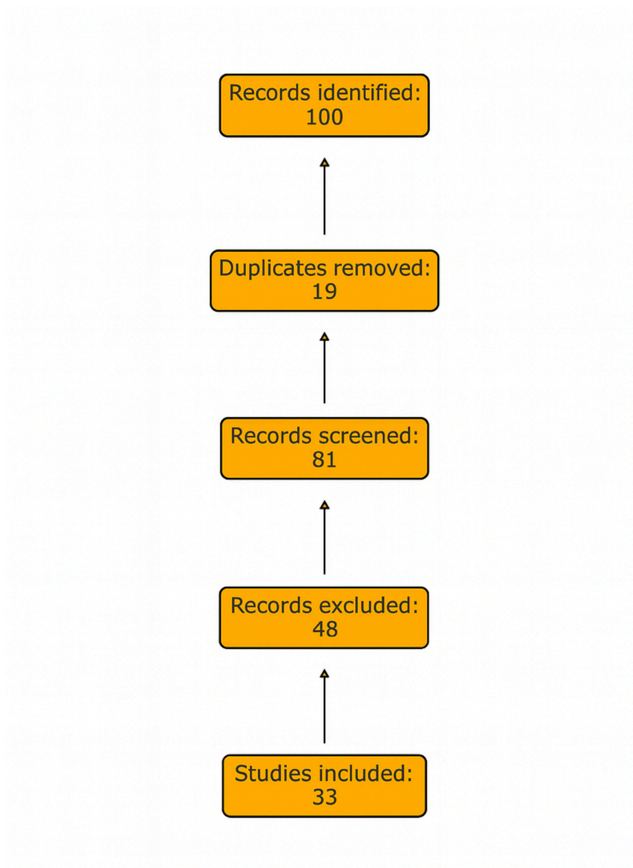

Figure 4. PRISMA flow diagram
The diagram depicts a vertical sequence summarising each stage of the literature-selection process:
Records identified: 100 – the top box, representing the total references exported from Zotero library.
Duplicates removed: 19 – a second box showing how many duplicate titles were detected and deleted.
Records screened: 81 – the remaining items subjected to the inclusion/exclusion criteria.

Records excluded: 48 – studies discarded for at least one disqualifying reason (e.g., non‑empirical, review article, grey‑infrastructure focus, etc.).
Studies included: 33 – the bottom box, indicating the final set of empirical papers on living shorelines that meet every criterion.

2.4 Descriptive Characteristics of Screened Studies

In addition to eligibility screening, the geographic distribution of all initially reviewed studies was analyzed to assess global representation. The majority of these studies were concentrated in North America, while fewer focused on Asia, Australia, Africa, Central America, and Europe. Additionally, two studies had a global scope, and eighteen did not specify a study location. This distribution highlights a geographic bias in the literature, which may affect the generalizability of findings and underscores the need for expanded research in underrepresented coastal regions.

3 Results of Systematic Review: Efficacy of Living Shorelines

This section synthesizes findings from 33 studies that met the inclusion criteria, exploring how living shorelines perform across key outcome areas: erosion control, biodiversity and habitat enhancement, water quality improvement, and socio-economic benefits. Studies varied significantly in terms of geographic location, shoreline type, and design complexity, providing a rich but heterogeneous evidence base. While most studies affirm the effectiveness of living shorelines, variability in design, context, and measurement poses challenges for generalizing outcomes.

3.1 Overview of Included Studies

Following the initial database search, 100 records were retrieved, of which 33 items satisfied all inclusion criteria and were retained for full review (Figure 4). The earliest included study was published in 2008, and the most recent in 2025, showing a steady year-on-year increase in the use of the terms “living shoreline” and the broader synonym “nature-based solutions.”

Across the 33 studies, living-shoreline configurations ranged from simple marsh plantings to more complex hybrid installations that paired vegetation with structural elements, such as oyster reefs, coir logs, wooden or rock sills, and low-crested breakwaters. This typological diversity reflects the field’s shift toward combining ecological and engineering approaches to maximize shoreline stability and habitat value.

Geographically, the majority of the studies did not specify their study location in the title or metadata. However, among those that did, locations included North Carolina, Chesapeake Bay, Florida, and South Carolina, highlighting a concentration of research in the southeastern United States where shoreline management is a pressing concern.

Methodologically, the studies employed a mix of approaches: 14 relied on quantitative field measurements, three used modeling techniques, and three utilized qualitative or mixed-methods designs, including policy and stakeholder analysis. Many studies included longitudinal data collection to assess changes over time.

Common outcomes assessed included erosion control effectiveness, vegetation growth and survival, biodiversity enhancement (e.g., fish or invertebrate presence), and comparisons of cost-effectiveness versus traditional shoreline armoring. Several studies also emphasized co-benefits, such as improved water quality or increased community resilience to sea-level rise.

Together, these findings underscore the multifaceted role of living shorelines in promoting climate adaptation, ecological restoration, and sustainable coastal development. The following sections will further synthesize how these outcomes vary by implementation type and contextual conditions.

3.2 Erosion Control and Shoreline Stabilization

Across the reviewed studies, living shorelines were consistently associated with a reduction in lateral erosion, particularly in post-storm conditions. Their capacity to attenuate wave energy and stabilize sediment has proven especially valuable in high-energy environments, where traditional soft shoreline approaches often fail to perform effectively (Mitchell & Bilkovic, 2019). In these contexts, hybrid designs, which incorporate natural vegetation with structural elements such as oyster sills or breakwaters, emerge as the most effective configurations for erosion mitigation.

A notable contribution to this body of evidence comes from Polk and Eulie (2018), who assessed 17 living shoreline projects along North Carolina’s coast using real-time kinematic GPS data. The real-time kinetic GPS data revealed that the post-installation shoreline change rates of 12 project sites were significantly decreased at northern and southern sites with living shorelines (Polk & Eulie, 2018). The living shorelines surveyed averaged a lateral change of +0.015 m/year, indicating a stable shoreline or slight accretion, in contrast to the unprotected marshes, which eroded at a rate of -0.31 m/year (Polk et al., 2022). Polk et al. (2022) also used the data to report that living shorelines reduced lateral erosion by approximately 325% in 12 of the 17 experimental sites, which was attributed to wave damping by the sills and the stabilization of roots from the vegetation (Polk et al., 2022).

Interestingly, the adjacent control sites, where no direct shoreline interventions were made, also exhibited reduced erosion, which the authors cautiously hypothesize may reflect spillover benefits from the broader regional implementation of living shorelines. However, this interpretation is tempered by methodological limitations and unmeasured environmental variables, illustrating the complexity of isolating shoreline dynamics in field studies.

Despite these positive trends, five of the evaluated living shoreline projects exhibited increased erosion rates post-installation. Polk and Eulie (2018) attribute these outcomes to potential design and placement flaws, such as close proximity to intensive human activity and suboptimal construction techniques. Their study highlights the crucial role of site selection, installation quality, and contextual factors, including hydrodynamics, sediment type, and shoreline slope, in determining the effectiveness of the project. Mitchell and Bilkovic's (2019), research further supports this point asserting that living shoreline effectiveness relies on incorporating the full suite of natural shoreline processes into their design. Furthermore, the variability in project age and sill design across their dataset complicates efforts to draw standardized conclusions, reinforcing the call for long-term, controlled monitoring frameworks.

Additional regional studies reinforce these themes. In the Chesapeake and Delaware Coastal Bays, Currin (2019) observed that hybrid living shorelines facilitated significant sediment accretion and fostered marsh vegetation density comparable to that of natural reference sites. Along the Gulf Coast, the integration of oyster reefs into shoreline design led to a measurable reduction in marsh-edge erosion, with average rates declining to approximately 1.0 m/year, compared to 1.3–2.5 m/year at unprotected sites (Currin, 2019, p. 1042).

Building on this topic, Sun et al. (2024) conducted a comparative analysis of a mature hybrid living shoreline and a natural marsh in Maryland's Coastal Bays. The storm event monitoring revealed distinct erosion mechanisms: the living shoreline experienced degradation due to pond expansion behind the rock sill, whereas the natural marsh eroded as a result of scarp undercutting, which occurs when the toe of the scarp becomes eroded, leaving a mass of unstable sand (Bond et al., 2023). Their sediment analysis revealed that the living shoreline contained coarser particles, lower organic content, and sparse vegetation, which may impact resilience (Sun et al., 2024). Further modeling efforts suggested that elevated bed shear stress during flood and ebb tides, on the landward edge of the sill, exacerbated marsh boundary scouring and sediment transportation (Sun et al., 2024).

Community-led efforts have also demonstrated the capacity of living shorelines to deliver meaningful stabilization outcomes under both typical and extreme conditions. In Cedar Key, Florida, three retrofitted living shoreline projects were constructed to reinforce deteriorating coastal infrastructure and restore ecological function along Daughtry Bayou (Barry et al., 2025). Multi-year monitoring showed that these interventions significantly reduced the extent of armored shoreline in direct contact with tidal forces, softening over 30% of the shoreline (Barry et al., 2025). Additionally, vegetated habitat areas increased at all three sites despite periodic sediment loss in higher-elevation zones caused by repeated hurricane impacts. Most notably, the living shorelines reduced wave energy by 33% to 79% during typical conditions and by up to 28% during Hurricane Idalia, consistently outperforming armored shorelines even under extreme stress. Barry et al. (2025) note that while the retrofits have persisted through several major storm events and continue to deliver erosion control and habitat benefits, the long-term viability of such projects may be challenged by sea-level rise, upland armoring, and intensifying storm regimes.

These findings collectively suggest that while living shorelines are generally effective in mitigating erosion, their performance is strongly influenced by site-specific factors, including hydrodynamics, material selection, vegetation type, and installation techniques. Despite using field studies and modeling data to refine current understandings of the erosion mitigation abilities of living shorelines, the design, and placement of living shorelines must be tailored to local environmental conditions. Future research should prioritize standardized monitoring protocols and long-term assessments to inform implementation practices more effectively.

3.3 Biodiversity and Habitat Support

Based on the reviewed literature, living shorelines consistently demonstrated the ability to enhance habitat complexity and ecological function across various geographies, design types, and restoration ages. Numerous studies highlight that replacing or removing hard structures and favoring nature-based solutions supports increased biodiversity.

Toft et al. (2021) conducted a comprehensive spatial study of 30 Beach sites in the Salish Sea, Washington state. In the study, they compared restored shoreline beaches with armored and natural reference sites. Their findings showed that 19 out of the 27 ecological and physical metrics differed significantly across site types. The metrics ranged from beach stability to ecological diversity to food web support for juvenile salmon (Toft et al., 2021). The restored sites had greater organic matter accumulation and biodiversity, improved beach structure, and more abundant invertebrate assemblages than armored sites. However, they were slightly lower than those of natural reference sites.

In particular, talitrid amphipods, a key player in shoreline food webs, were found to be more abundant at the restored and reference sites compared to the armored shorelines (Toft et al., 2021). Stable isotope analysis confirmed their diets were dominated by marine algae and eelgrass, food sources that are better supported by natural and restored wrack zones. The primary food source for the talitrid amphipods and their ecological preference emphasizes the importance of substrate and organic matter availability in facilitating trophic connectivity along shorelines (Toft et al., 2021). To gather further information on insect diversity as it relates to living shorelines, vegetative structures were analyzed, looking at overhanging vegetation and driftwood (Toft et al., 2021). These vegetative structures were chosen for analysis as they support higher terrestrial insect diversity, which in turn is an important food source for juvenile salmon and other species; therefore, they act as an indicator of greater species biodiversity. Moreover, the richness of insect taxa and the presence of plant growth on logs were shown to increase over time since restoration, suggesting positive ecological trajectories over a 4–7-year period.

Research by Gittman et al. (2016) further supports the ecological value of living shorelines, showing that marsh-sill systems not only outperformed hardened shorelines but also exceeded natural marshes in their ability to support fish and crustacean (nekton) abundance and diversity. These benefits were particularly evident three or more years after construction, highlighting the importance of monitoring long-term ecosystem service trajectories. Living shorelines with sill structures were also found to support greater cover of filter-feeding bivalves, offering both refuge and food resources to nekton communities.

Long-term data reinforce the importance of sustained monitoring to understand the full ecological impacts of living shorelines. Smith et al. (2024) conducted a Before-After-Control-Impact (BACI) study across four sites in North Carolina, examining nekton responses over a period of four to five years post-installation. They found that living shorelines either equaled or outperformed natural marshes in terms of nekton biomass, abundance, and richness at two of the four sites, specifically those with granite rock sills. In contrast, sites constructed with oyster bag sills showed little to no enhancement, highlighting that material choice has a significant influence on ecological outcomes. Notably, the study observed that many environmental benefits, particularly for nekton communities, emerged gradually over time, underscoring that short-term assessments may underestimate the performance of living shorelines.

Supporting findings from other regions, Than and Hague (2024) reported biodiversity gains from the re-establishment of native species at research sites across living shoreline projects in New York, Washington, and Florida, attributing success to habitat restoration features integrated into project designs. La Peyre et al. (2022) similarly observed that oyster-based shoreline installations enhanced nekton biodiversity by providing foraging and nursery habitats. Conversely, Currin (2019) noted that hardened shorelines (bulkheads and riprap) were associated with reduced faunal utilization and overall habitat degradation in the Chesapeake and Delaware Coastal Bays, having significant impacts on biodiversity within the hydric features and ultimately affecting overall productivity.

Beyond temperate environments like the Chesapeake Bay, living shoreline strategies have also been applied in tropical and subtropical systems, where their interaction with mangrove habitats presents additional considerations for biodiversity and shoreline stability. Recent studies in Australia of hybrid mangrove living shorelines have found that rock fillets not only stabilize eroding banks but also facilitate mangrove establishment in areas with limited prior vegetation cover (Morris et al., 2024). At the estuary scale, these interventions contributed to increased habitat complexity and reduced sedimentation, outcomes linked to improved water quality and biodiversity. However, the effectiveness of erosion control and habitat enhancement varied considerably at the site level.

Additional evidence from coastal Alabama highlights both the potential and the limitations of using community-level metrics to assess habitat enhancement outcomes. De Barros et al. (2023) evaluated nekton assemblages across eight living shoreline sites and nearby controls, finding generally higher abundance, species richness, and diversity at living shorelines and adjacent control sites compared to hardened shorelines. However, no apparent differences emerged between the restored and adjacent unrestored shorelines, suggesting possible ecological equivalence or limitations in the sensitivity of standard community metrics. The authors emphasize the need for more refined indicators, such as individual-based metrics like growth rates or body condition of key species, to detect the impacts of restoration and better inform project evaluation. Similarly, Amato et al. (2022) conducted an experimental study in the Northern Gulf of Mexico to assess the ecological functionality of small-scale salt marsh plantings on residential and recreational properties impacted by significant wave energy. In the study locations, protective coir logs were placed; however, the researchers observed that the black needlerush (Juncus *roemerianus*) plantings declined or remained unchanged over the two-year study period. The study found no meaningful differences in nekton abundance or soil slope between planted and control plots and observed restricted growth of submerged aquatic vegetation (SAV) in front of the planted areas, possibly due to unintended impacts from the coir logs. These findings reinforce that while living shorelines can provide ecological value comparable to that of natural sites, understanding the subtle or long-term effects may require more targeted ecological monitoring approaches. Additionally, in high-energy environments, small-scale plantings alone may not achieve meaningful ecological restoration unless accompanied by effective wave attenuation and careful consideration of the interactions with adjacent habitats.

In addition to supporting intertidal biodiversity, living shorelines may also influence submerged aquatic vegetation (SAV) communities adjacent to project sites. Research by Palinkas et al. (2023) suggests that when properly designed, living shorelines can enhance conditions for SAV by reducing wave energy. However, the inclusion of rock sills and other structural components may alter sediment transport in ways that either enhance or inhibit SAV growth, depending on site-specific conditions.

These studies demonstrate that living shorelines, particularly those that incorporate structural habitat elements and are allowed time to mature, are effective at supporting biodiversity and restoring coastal ecosystem functions. However, variability in project design, site conditions, and monitoring approaches continues to shape the degree and pace of ecological recovery.

3.4 Water Quality and Ecosystem Services

Living shorelines demonstrate a measurable capacity to improve water quality and support essential ecosystem services, including nutrient cycling, sediment retention, and carbon sequestration. La Peyre et al. (2022) found that constructed oyster reefs within living shoreline systems not only stabilized adjacent shorelines but also enhanced water filtration and nitrogen cycling. Similarly, Currin et al. (2008) observed that marsh-based living shorelines promoted the accumulation of organic matter and nutrient retention, particularly in low- to moderate-energy systems. Morris et al. (2018) emphasized, in a comparative review of nature-based and gray shoreline solutions, that living shorelines offer a wide range of co-benefits, including pollutant filtration and long-term carbon sequestration.

Building on these findings, Onorevole et al. (2018) conducted a chronosequence study in North Carolina that revealed nitrogen removal through denitrification increased substantially within the first seven years after installation. Denitrification efficiency exceeded 50% at all sites, with several surpassing 75%, indicating net nitrogen removal without the tradeoff of increased nitrous oxide emissions. Notably, these biogeochemical benefits were consistent across habitat zones, including oyster reefs, salt marshes, and adjacent sandflats, suggesting that living shorelines operate as integrated ecological units capable of delivering substantial water quality improvements in relatively short time frames. However, Schoell et al. (2023) cautions that the denitrification enzyme of newly created marsh zones, may differ from pre-existing marshes. The short-term study carried out by Schoell et al (2023) found that denitrification enzyme activity rates were higher at living shoreline sites compared to the control sites, and that rates did not change significantly over time.

Long-term monitoring by Palinkas et al. (2023) in the Chesapeake Bay further supports the role of living shorelines in nutrient retention. While sedimentation rates were similar between intertidal and subtidal zones, particulate carbon (PC) and particulate nitrogen (PN) burial rates were significantly higher in marsh habitats adjacent to living shorelines than in neighboring subtidal areas. This distinction was not observed at reference sites without living shorelines, indicating that the vegetated marsh component plays a dominant role in total nutrient storage, often contributing more than 90% of it. Davis (2015), additionally support that living shorelines play an important role in nutrient retention observed high carbon sequestration rates in marshes ranging from 12 to 38 years old, noting sequestration rates dropped with increased age. Regarding water quality, living shorelines are often cited for their ability to improve clarity and filtration following installation (Smee, 2019). Similarly, Palinkas et al. (2023) reported a noticeable increase in water clarity at their study sites. These results highlight the compounded benefits of vegetated shoreline features in promoting both nutrient sequestration and improved optical water quality.

3.5 Socio-economic benefits

In alignment with the three pillars of sustainability, environmental, economic, and social, living shorelines offer numerous co-benefits that extend beyond ecological resilience. By promoting healthy coastal and marine ecosystems, living shorelines also support opportunities for sustainable coastal and marine tourism by enhancing natural aesthetics, biodiversity, and recreational access (Arkema et al., 2017). As of 2018, ocean-based tourism and recreation in the United States employed 2.5 million people and generated $143 billion in gross domestic product (National Oceanic and Atmospheric Administration, Office for Coastal Management, n.d.). Habitat improvements associated with living shoreline installations have been linked to increased fishery success, which may lead to greater recreational satisfaction among both residents and tourists (Arkema et al., 2017).

From an economic perspective, living shorelines can protect property values by mitigating erosion and buffering storm impacts while also reducing long-term maintenance costs relative to hardened structures. Additionally, these projects contribute to local economies by generating employment opportunities in planning, construction, monitoring, and maintenance (Sutton-Grier et al., 2015). In cases where oysters are integrated into living shoreline design, the added ecosystem service value can be substantial. For example, oyster-based living shorelines have been estimated to provide over $6,700 annually in nitrogen removal services alone (Arkema et al., 2017).

Taken together, the environmental, economic, and social co-benefits of living shorelines underscore their value as a nature-based solution that aligns with sustainability and climate resilience goals. While empirical evidence demonstrates their multifaceted effectiveness, particularly in ecological and socio-economic domains, further critical reflection is needed to interpret these findings in the broader context of shoreline management. The following section discusses the implications of these results, identifies persistent gaps, and explores opportunities for scaling up the use of living shorelines.

4 Discussion

The systematic review of 33 peer-reviewed studies highlights a growing global concern over coastal erosion and a strengthening consensus on living shorelines as an effective, nature-based solution. These approaches are particularly valuable in addressing both erosion and biodiversity loss, especially as communities confront increasing pressure from 'coastal squeeze' and weigh the trade-offs between hard and living shoreline strategies. The findings of this review further affirm the ability of living shorelines to deliver multiple important co-benefits. Across diverse geographic and energy settings, living shorelines, particularly hybrid designs, were consistently associated with reductions in lateral erosion and improvements in shoreline stability. These outcomes were especially notable in high-energy environments, where traditional soft approaches often fail to withstand wave action. As observed in Polk and Eulie (2018), project effectiveness is shaped not only by design but also by environmental context, with poorly sited or improperly constructed projects exhibiting erosion or limited success. This underscores the need for rigorous site assessment and long-term monitoring.

Biodiversity and habitat support emerged as key ecological benefits of living shorelines. Studies Gittman et al. (2016) and Toft et al. (2021) found that living shorelines support nekton abundance, trophic connectivity, and shoreline complexity at levels comparable to natural marshes. However, material selection and structural components (rock vs. oyster sills) influence the extent of these benefits (Smith et al., 2024). Temporal scales also have significance regarding living shoreline projects as ecological enhancements often develop over several years. Highlighting the importance of sustained, long-term monitoring to fully capture ecosystem dynamics and trajectories.

Water quality improvements, particularly nutrient cycling, were well-documented, while findings varied by site and study design. Onorevole et al. (2018) demonstrated significant denitrification efficiency increases in the years after installation, while Schoell et al. (2023) highlighted that short-term monitoring may not properly capture the nutrient removal potential of newly created marsh zones. However, the higher denitrification activity most likely reflects pre-existing marsh capacity, emphasizing the complex nature of measuring outcomes across varied habitat zones and project stages.

Beyond ecological performance, living shorelines contribute to a range of socio-economic co-benefits. They have been found to enhance recreational value, support fisheries, buffer storms, and reduce costs compared to hard shorelines (Arkema et al., 2017; Sutton-Grier et al., 2015), aligning with overarching sustainability and climate adaptation goals. However, the long-term viability of living shorelines remains largely dependent on adaptive design strategies that account for sea level rise and intensifying storms. Climate-informed site selection frameworks such as the one proposed by Parkinson et al. (2024) represent an important approach to meeting this need. Similarly, Polk et al. (2022) emphasize that performance is closely tied to design and site-specific variables, reinforcing the need for tailored interventions rather than one-size-fits-all solutions.

Several studies emphasize the importance of context, as the effectiveness of living shoreline interventions depends on factors such as wave energy, sediment type, vegetation structure, and sea level trends (Toft et al., 2021; Hsiung et al., 2025). Site selection and design remain critical determinants of living shoreline performance, particularly in the face of accelerating sea level rise. Parkinson et al. (2024) highlight the need for climate-informed planning by introducing a site selection and design tool that incorporates sea level rise projections to guide the placement and configuration of living shoreline projects. This proactive approach emphasizes the value of forward-looking strategies in enhancing long-term effectiveness.

Together, the findings of the 33 records reviewed suggest that while living shorelines are broadly effective, their success is not guaranteed. Instead, it is reliant on a combination of ecological understanding, engineering design, site conditions, and climate preparedness.

Future research should prioritize long-term, standardized monitoring across diverse contexts to better inform living shoreline best practices and optimize outcomes across ecological, physical, and socio-economic dimensions.

4.1 Limitations

While this systematic review synthesizes current knowledge on the effectiveness of living shorelines, several limitations should be acknowledged. First, there is a notable geographic bias in the literature, with a concentration of studies conducted in the eastern United States, particularly in the Mid-Atlantic and Southeastern coastal regions. This may limit the generalizability of findings, as they may not fully capture performance in other contexts, such as arid coastlines, tropical systems, or areas with differing regulatory and geomorphological conditions.

Second, there was significant variation in study design and monitoring duration, which complicates efforts to standardize conclusions. Some studies employed well-rounded, long-term monitoring frameworks (e.g., BACI or chronosequence designs),while others relied on short-term or opportunistic sampling. This variation also affects the detection of ecological trajectories, namely biodiversity gains or biogeochemical improvements.

Third, there is an inherent publication bias to highlight successful projects. Unpublished data, gray literature, or projects that did not yield positive results may be underrepresented, potentially skewing the perceived effectiveness of living shoreline interventions.

Lastly, inconsistent biodiversity, water quality, and socio-economic outcome metrics make it difficult to accurately quantify co-benefits across studies. While erosion reduction and sediment stabilization are relatively straightforward to measure, ecological and community-level benefits are often evaluated through diverse methods, indicators, and spatial scales, reducing the potential for meta-analysis.

These limitations highlight the need for standardized monitoring protocols, more geographically diverse case studies, and climate-integrated design frameworks to strengthen future evaluations of living shoreline performance.

5 Conclusion

This capstone project examined the role of living shorelines as a sustainable and adaptive solution to coastal erosion, sea-level rise, and habitat degradation. Drawing on a systematic review of existing literature, policy frameworks, and case studies, the findings demonstrate that living shorelines can provide ecological, social, and economic benefits when implemented thoughtfully and effectively. Unlike traditional hardened structures, these nature-based approaches support shoreline stabilization while preserving or enhancing coastal ecosystems.

As coastal communities continue to face intensifying environmental pressures, prioritizing solutions that balance protection with ecological function is essential. This study contributes to a growing body of work advocating for integrative, science-informed approaches to shoreline management, which consider not only engineering feasibility but also ecological sustainability and community resilience.

Moving forward, living shoreline practitioners should:

- Prioritise climate-informed design tools (Parkinson et al. 2024)
- Emphasize long-term monitoring
- Favor hybrid approaches, particularly in high-energy settings
- Consider community-scale implementation for all project scales
- Improve site-specific material selection and implementation

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7 Appendices

7.1 Appendix A: Search Strategies and Terms

The following search string was used to identify relevant peer-reviewed literature for inclusion in the systematic review:

Search Terms:
(“living shoreline” OR “living shorelines” OR “nature-based solutions”) AND (“effective” OR “effectiveness”)

This Boolean search string was applied across multiple academic databases, including Google Scholar, Web of Science, and Scopus. The goal was to capture studies evaluating the performance, outcomes, or comparative advantages of living shorelines or similar nature-based coastal protection strategies. Filters were applied to include publications between 2000 and 2025 and written in English. Studies were screened based on title and abstract for relevance, with eligible full texts reviewed for empirical evidence addressing erosion control, habitat enhancement, water quality, or socio-economic outcomes.

7.2 Appendix B: List of excluded studies with reasons

Publication Year	First Author	Title	Database	Reason for Exclusion
2021	Rashidi	Coastal Structures as Beach Erosion Control and Sea Level Rise Adaptation in Malaysia: A Review	Consensus	Excluded in 2nd round, not really about living shoreline effectiveness
2020	Smith	Coming to Terms With Living Shorelines: A Scoping Review of Novel Restoration Strategies for Shoreline Protection	Google Scholar	Systematic Review; No data on shoreline effectiveness to extract; will be used as a reference
2018	Tavva	Development of Shoreline Response Assessment System for Planning Sustainable Shore Protection Measures	Consensus	No mention of living shoreline
2022	Nunez	A geospatial modeling approach to assess site suitability of living shorelines and emphasize best shoreline management	Google Scholar	Model analysis, no real analysis on effectiveness of living shorelines

		practices		
2024	Papasarafianou	A Holistic Approach for Coastal–Watershed Management on Tourist Islands: A Case Study from Petra–Molyvos Coast, Lesvos Island (Greece)	Consensus	No mention of living shoreline
2022	Pradhan	Coastal erosion: a threat to sea turtle nesting habitat, east coast of India	Consensus	No mention of living shoreline
2024	Benhur	Coastal resilience and shoreline dynamics: assessing the impact of a hybrid beach restoration strategy in Puducherry, India	Consensus	Hard shoreline study
2018	Tavva	Development of Shoreline Response Assessment System for Planning Sustainable Shore Protection Measures	Consensus	No data on effectiveness of *LS as a treatment; system development
2018	Josephs	Identifying social factors that undermine support for nature-based	Scopus	No data on effectiveness of *LS as a treatment

		coastal management.		
2022	Castillo	Shoreline Change Analysis Using Historical Multispectral Landsat Images of the Pacific Coast of Panama	Consensus	No living shoreline data
2023	Ankrah	Shoreline Change and Coastal Erosion in West Africa: A Systematic Review of Research Progress and Policy Recommendation	Consensus	No data on effectiveness of *LS as a treatment; literature review
2020	Scyphers	Designing effective incentives for living shorelines as a habitat conservation strategy along residential coasts	Google Scholar	Homeowner perception vs. info on the effectiveness of *LS & **NbS
2022	Jones	Towards principles and policy levers for advancing living shorelines	Google Scholar	Review/conceptual/editorial
2016	O'Donnell	Living Shorelines: A Review of Literature Relevant to New England Coasts | Journal of Coastal	Google Scholar	Review/conceptual/editorial

		Research		
2024	Dario	Shaping coastal nature-based solutions: Perceptions and policy priorities of living shorelines	Google Scholar	Review/conceptual/editorial
2022	Hopkins	The Emerald Tutu: Floating Vegetated Canopies for Coastal Wave Attenuation	Google Scholar	No data on effectivness of *LS as a treatment
2018	Lafortezza	Nature-based solutions for resilient landscapes and cities	Google Scholar	No data on effectivness of *LS as a treatment
2021	Elshazly, A.	Nature Based Solutions for Coastal Adaptation to the SLR: A Case Study from the Northwest Mediterranean Coast of Egypt	Google Scholar	Excluded in 2nd round, not really about living shoreline effectiveness
2020	Stafford	Encouraging Living Shorelines over Shoreline Armoring: Insights from Property Owners Choices in the Chesapeake Bay	Google Scholar	Excluded in 2nd round, not really about living shoreline effectiveness
2022	Francis	Equivocal associations between	Google Scholar	focuses on the ecological effects of armor

		small-scale shoreline restoration and subtidal fishes in an urban estuary.		removal in Puget Sound and does not explicitly study living shoreline techniques
2024	Coleman	Quantifying the impacts of future shoreline modification on biodiversity in a case study of coastal Georgia, United States	Google Scholar	predictive models to estimate potential biodiversity impacts of future shoreline development
2016	Gittman	Ecological Consequences of Shoreline Hardening: A Meta-Analysis	Google Scholar	Hard shoreline study
2024	Boyd	A Step by Step Shoreline Attribute Analysis for Selected Waterbodies in the Gulf of Mexico to Promote the Use of Living Shorelines	Google Scholar	Predictive study; site selection
2019	Brandon	A Wall Impervious to Facts: Seawalls, Living Shorelines, and the U.S. Army Corps of Engineers' Continuing Authorization of Hard Coastal	Google Scholar	It does not present original empirical data on living shoreline effectiveness.

		Armoring in the Face of Sea Level Rise		
2025	Baker	Co-Funding Robust Monitoring with Living Shoreline Construction is Critical for Maximizing Beneficial Outcomes	Google Scholar	No data on effectiveness of *LS as a treatment
2013	LC Protection, R Authority	Living Shoreline Demonstration Project	Google Scholar	Citation only
2024	Ficzkowski	Enhancing Climate Resiliency Through Improving Ecosystem Services in Shoreline Municipalities – Lessons from Canada	Google Scholar	Lacks measured outcomes of specific living shoreline projects
2021	Fillyaw	Strategies for successful mangrove living shoreline stabilizations in shallow water subtropical estuaries	Google Scholar	Lacks measured outcomes of specific living shoreline projects
2016	Yepsen	A Framework for developing monitoring plans for coastal	Google Scholar	Lacks measured outcomes of specific living shoreline

		wetland restoration and living shoreline projects in New Jersey		projects
2016	Zylberman	Modeling site suitability of living shoreline design options in Connecticut	Google Scholar	No data on effectivness of *LS as a treatment
2018	Berman	Implementing sustainable shoreline management in Virginia: Assessing the need for an enforceable policy	Google Scholar	No data on effectivness of *LS as a treatment
2021	Gittman	Reversing a tyranny of cascading shoreline-protection decisions driving coastal habitat loss	Google Scholar	No data on effectivness of *LS as a treatment
2018	Antoine	Increasing Living Shoreline Implementation in Virginia: Legal and Policy Recommendations	Google Scholar	Lacks measured outcomes of specific living shoreline projects
2021	Ruggiero	Assessing living shoreline feasibility at a remote site influenced by ship wake: a case	Scopus	Feasibility study

		study at Pea Patch Island on the Delaware River		
2023	Loizzo	Restore the shore: online STEM engagement impacts on youths' conceptualizations of living shorelines and connection to water	Scopus	Education focus, not shoreline performance
2015	Kochnower	Factors influencing local decisions to use habitats to protect coastal communities from hazards	Scopus	Focus on Decision-Making, Not Intervention Outcomes
2022	Hernandez	Selling New Jersey Landowners on Living Shorelines as the Superior Method for Coastline Protection	Scopus	Policy suggestions, not shoreline performance focus
2018	Kinney	Shoreline Armoring Vital Sign Base Program Analysis	Scopus	Regulatory update on shoreline armoring
2023	Parker	Creating Land with Artificial Oyster Rings: Legal Challenges	Scopus	Legal research; not performance focused

		from State Owned Bottom Land to Living Shorelines		
2021	Hardaway	Living shoreline design guidelines for shore protection in Virginia's estuarine environment	Scopus	Design guidelines
2006	Luscher	Regulatory Process for Living Shoreline Implementation in Maryland	Scopus	Policy/Process Analysis
2016	Carrion	Determining factors that influence smooth cordgrass (Spartina alterniflora Loisel) transplant success in community-based living shoreline projects	Scopus	Narrow outcome focus—does not assess shoreline stability or ecosystem-level effects.;No comparative or baseline data to assess intervention effectiveness.
2024	Wetzler	Challenges and Solutions to Permitting Living Shoreline Projects	Scopus	Policy suggestions, not shoreline performance focus
2024	Rupasinghe	Sustainable oyster shell incorporated artificial reef concrete for living shorelines	Scopus	Focus on Material Properties, Not Shoreline Function

2023	Biber	Assessing the Effectiveness of Seagrass Detection Using Drone and Sonar Based Methods	Scopus	No data on the effectiveness of *LS as a treatment
2020	Zhu	Aquaculture farms as nature-based coastal protection: Random wave attenuation by suspended and submerged canopies	Scopus	No data on effectiveness of *LS as a treatment
2015	Scyphers	Participatory Conservation of Coastal Habitats: The Importance of Understanding Homeowner Decision Making to Mitigate Cascading Shoreline Degradation	Scopus	Focus on Social Decision-Making , Not Shoreline Performance

*LS = Living Shoreline **Nbs = Nature based solution