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Future-oriented coastal protection: The utility of living shorelines under changing climatic conditions

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ABSTRACT

An accumulation of novel nature-based shoreline management techniques have developed over the past two decades out of the continued need to protect waterfront land combined with an awareness of the relationship between healthy coastal ecosystems and human societies. Shoreline protection strategies such as living shorelines incorporate these nature-based approaches to simultaneously enhance ecosystem functioning while providing shoreline stabilization benefits. The continued role of these approaches into the future, however, will be challenged by a rapidly changing coastal environment. While living shorelines have received global attention and integration into climate policy and governance frameworks, the ability of shoreline systems to withstand future climate extremes remains uncertain. It is critical to consider not only what works in the present, but what will work decades from now. This paper reviews the current state of knowledge regarding the response of natural coastal ecosystems and living shorelines to climate change, including increasing storminess, sea-level rise, altered seawater properties, and shifting biotic interactions. We then consider the future role of living shorelines within the broader framework of existing coastal adaptation strategies and propose a framework of principles towards increasing their sustainability in the context of dynamic and evolving coastal challenges. We argue that extending the relevance and effectiveness of living shorelines in a changing climate depends on an improved understanding of living shoreline function across diverse environments, the incorporation of forward-looking design strategies, a coordinated, holistic planning approach, and the integration of maintenance and adaptive interventions.

NBS Impacts and Implications

- This paper examines the impacts of climate stressors on both natural coastal systems and living shorelines. It offers guidance for enhancing their ecological resistance and recovery to improve the long-term sustainability of living shoreline interventions under uncertain climate futures.
- This paper advances four forward-looking principles to support the long-term viability of living shorelines as a climate resilience strategy. These principles aim to reduce lifecycle burdens, improve implementation efficiency and efficacy, and better align living shorelines with the resource constraints and dynamic conditions inherent to coastal zone management.

1. Introduction

Coastal ecosystems provide critical services that support both ecological and human communities. Shoreline protection is one such service, delivered largely through wave attenuation and sediment stabilization provided by coastal habitat features such as intertidal wetland vegetation [1,2]. Since the 1900s, an estimated 63 % of coastal wetlands have been lost [3], a decline driven by increasing infrastructure, alteration of hydrological features, and land reclamation [4,5]. Coral and shellfish reefs similarly aid in shoreline defense [6,7], but large-scale global declines in many reef-forming species have also reduced their structure and extent, diminishing their protective capacity [8–10]. Anthropogenically driven climate change exacerbates these losses, compounding effects of both acute disturbances like coastal storms and chronic stressors like sea-level rise and changing seawater parameters.

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As coastal regions experience heightened extreme weather [11,12], flooding events [13–15], and increasing sea level [16], effective coastal zone management is increasingly imperative to reduce risk for both human societies and natural habitats.

Coastal defense is one of several coastal adaptation strategies, aimed at reducing hazard risk by stabilizing shorelines and reinforcing infrastructure [17,18]. Such defense can take many forms, ranging from traditional hard armoring to nature-based approaches. Hard armoring involves engineered structures, such as seawalls and bulkheads, designed to shield shorelines from erosion and the effect of storms. In contrast, coastal nature-based protection involves nature and natural processes to reduce coastal hazard risks [19,20]. The term "living shoreline" has gained popularity in the United States to refer to nature-based techniques in low to intermediate energy coastal systems to protect upland property and infrastructure while also supporting habitat and ecosystem processes [21]. Though varied in design/ materials and project goals, living shorelines share the primary objectives of shoreline stabilization, erosion control, and storm protection (Fig. 1). Coastal defense techniques under this definition have become integrated into coastal management strategies across North America, Asia, and Europe, but may be known by a variety of alternative names [22]. These approaches differ from traditional ecological restoration as their primary objective is to maximize shoreline protection rather than facilitate ecosystem recovery. Living shorelines use a variety of stabilization practices that range from natural approaches to hybrid techniques that integrate engineered structures into design (Fig. 1). Common design components include planting of native vegetation, addition of sediment, and placement of nearshore wave break structures (Fig. 2), such as oyster reefs (e.g., bagged oyster shell, assorted artificial oyster reef substrates) or rock sills [22,23].

In contrast to hard armoring, living shorelines promote ecosystem functions such as carbon storage, water quality improvement, and fish habitat provisioning [24,25]. Beyond their ecological functions, emerging analyses show living shorelines and other nature-based measures can generate benefits by avoiding costs associated with damage, reduced infrastructure expenditures, and the increased economic value of ecosystem services including fisheries and recreation when compared to hard stabilization methods [26–31]. Such studies underscore the co-benefits of living shorelines, however, many questions remain regarding their performance under various environmental conditions over time. Addressing these uncertainties is key to ensuring that living shorelines provide habitat and shoreline protection benefits, function sustainably, and are adopted widely [32]. Many previous studies have demonstrated the ability of living shorelines to meet immediate shoreline management needs (e.g., [33–35]). Our objective is to evaluate the future utility of living shorelines as a coastal resilience strategy. We begin by reviewing current knowledge on the response of living shorelines to major climate stressors, including altered storm regimes (Section 2.1), sea-level rise (Section 2.2), changes in seawater properties (Section 2.3), shifting species interactions (Section 2.4), and the multiplicative effects of multiple stressors (Section 2.5). We establish a baseline understanding of the predicted sustainability of living shorelines in response to each stressor (Table 1), where sustainability includes both ecological resistance (i.e., ability to withstand change when subject to a disturbance [36]) and recovery (i.e., the speed at which a system returns to equilibrium after a perturbation [37]). Given the concentration of living shoreline research in North America [22], our synthesis necessarily draws heavily from this focus while also incorporating insights from natural analog systems and comparable nature-based interventions globally. For cases where living shoreline data are limited, we focus primarily on vegetated intertidal wetlands (salt marsh and mangrove habitat) and shellfish reefs (oyster reefs and mussel beds), acknowledging their broad geographic relevance, provision of protective services, and designation as target organisms for many living shorelines.

Building on this foundation, and recognizing that current function does not guarantee future effectiveness, we consider the future role of today's living shorelines within the broader suite of existing coastal resilience strategies, exploring both limitations and opportunities for improvement under climate change. We argue that enhancing the sustainability of living shorelines depends on an improved understanding of living shoreline function across environments (Knowledge Generation, Section 3.1), the incorporation of forward-looking design strategies (Designing for Change, Section 3.2), a coordinated, holistic planning approach (Strategic Implementation, Section 3.3), and integrating maintenance and adaptive interventions (Embracing Management, Section 3.4). Together, these principles chart a path forward for living shorelines to remain a viable component of coastal resilience under predicted future conditions.

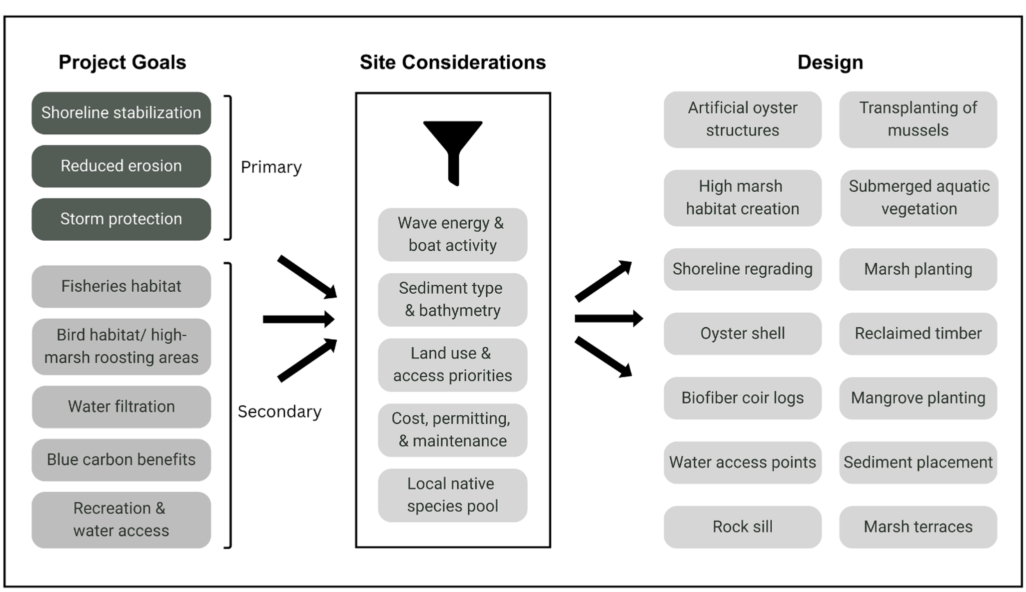

Fig. 1. Diagram depicting how living shoreline project goals connect to design components, with material and design choices filtered by site-specific constraints. Primary shoreline protection goals (dark grey) are shared across projects, but ecosystem service co-benefits (grey) are project specific.

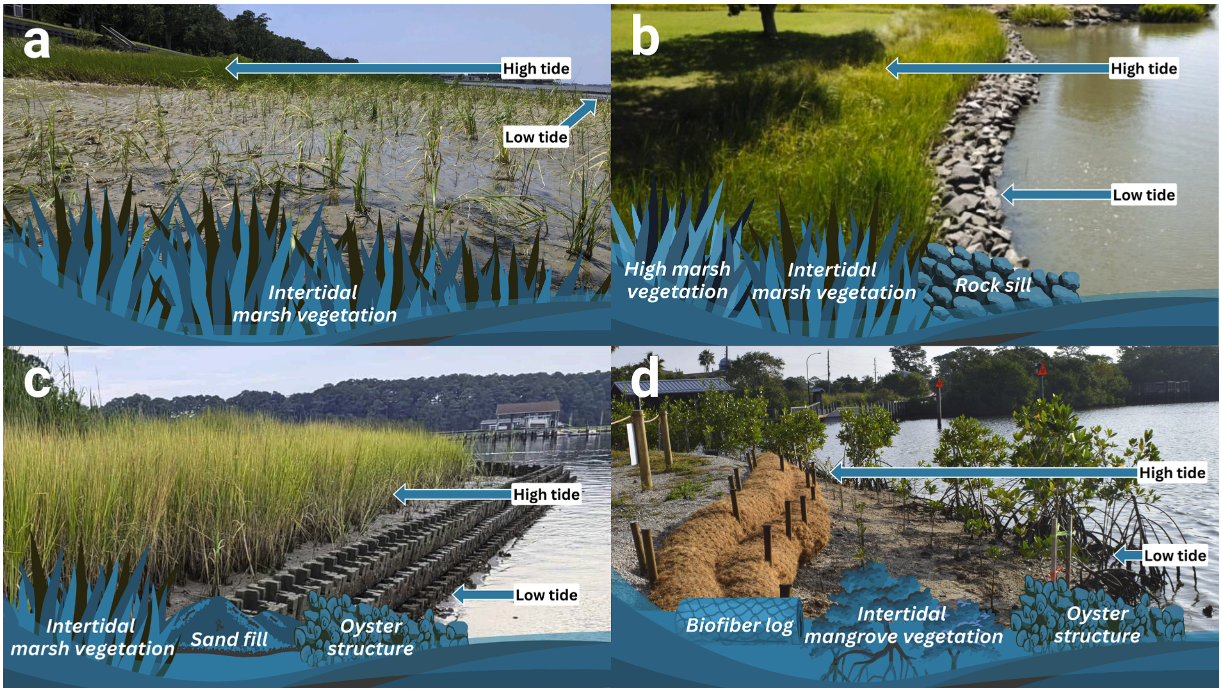

Fig. 2. Examples of living shorelines in North America that illustrate how the same terminology of 'living shoreline' can encompass a variety of materials, biota, and designs. A) Planted intertidal vegetation (*Spartina alterniflora*) on existing sandy substrate in the upper intertidal zone. B) Planted high marsh vegetation (*Spartina patens*) and intertidal *S. alterniflora* protected by a rock sill, image provided by CCRM-VIMS. C) *S. alterniflora* in sand fill with Oyster Castles as an oyster structure in the lower intertidal. D) Bank stabilization with biofiber coir logs and intertidal mangrove (*Rhizophora mangle*) planting paired with oyster shell bags in the lower intertidal (mostly submerged), image provided by Armando J. Ubeda.

Table 1
Summary of the main mechanisms that confer resistance (ability to withstand stress) and resilience (ability/time to recover) of natural coastal ecosystems and their relevance to living shoreline sustainability under major climate stressors.

Resistance Mechanisms	Recovery Mechanisms
Altered Storm Regimes (2.1)	
Wind protection through vegetative structure	Vegetative regrowth
Wave attenuation through vegetation, reef, or hybrid structures	Reef recruitment and regrowth
Substrate stabilization through vegetative-sediment interactions	Elevation gains through storm-driven sediment deposition
Sea-level Rise (2.2)	
Upland migration into low-lying adjacent habitats	Elevation gains through storm-driven sediment deposition
Vertical accretion through reef growth	Elevation gains through biomass production
Physiological acclimation/ tolerance	
Changes in Salinity, Acidification, and Temperature (2.3)	
Habitat heterogeneity and refugia	Vegetative regrowth
Interspecific functional redundancy	Reef recruitment and regrowth after acute stressors
Physiological acclimation/ tolerance	
Shifting Species Interactions (2.4)	
Interspecific functional redundancy	
Response diversity	
Physiological acclimation/ tolerance	
Interaction of Multiple Stressors (2.5)	
Draw on mechanisms described above for individual stressors	

2. Overview of climate effects and expected responses of coastal systems

2.1. Altered storm regimes

The high variability in living shoreline design, composition, environmental setting, and the resulting interactions among both natural and engineered components introduces significant complexity into the prediction of living shoreline sustainability in response to future storm climatology. Storms are a natural part of the disturbance ecology of coastal systems, acting through direct mechanical forces, like high wind and wave action, and indirect ecological stressors, such as altered hydrology and nutrient availability [38–40]. Despite decades of research on the response of coastal wetlands to extreme weather events, predicting the sustainability of these habitats at large spatial scales in the face of increased storm severity and frequency expected with climate change proves challenging. Increased frequency of severe weather events will further influence the sustainability of coastal systems. High frequency of natural disturbances across ecosystems have been linked to alterations in biodiversity, biomass, and community structure [41,42] as well as morphology [43]. In fact, a majority of lateral shoreline erosion can be attributed to high frequency, intermediate severity storms rather than those of greater magnitude but lower frequency [44]. Biota exposed to more frequent disturbances have less time to recover, and species with slower growth rates, such as woody mangrove species, will be especially vulnerable as damage from earlier storms may not be fully overcome before subsequent storm events occur.

Species-specific trait variation (e.g., morphology, growth rate), local site conditions (e.g., species composition, nearshore geomorphology), and storm characteristics (e.g., intensity, duration) influence an ecological system's response to severe storm events [45–47]. The structural and functional traits between and across mangrove and salt marsh species differentially influence resistance to wind and wave energy and affect post-disturbance resilience [48–53]. For example, vegetation resistance estimates in mangrove stands following the 2013 Typhoon Haiyan in the Philippines found that *Avicennia* and *Sonneratia* species exhibited 6.4 % and 5.4 % greater vegetative resistance, respectively, than *Rhizophora*, reflecting genus-specific differences in height, density, and diameter at breast height [54]. Beyond vegetation, storm-driven damage is of lower consequence for the low-profile growth form of shellfish beds; rather, climate change-induced salinity fluctuations, warming water temperatures, and water acidification are projected to exert substantial stress on reef-building taxa [55–57] (See Section 2.3).

Storms can also induce significant landscape-scale changes to biogeomorphic parameters that control ecosystem structure and function, such as shifts in soil elevation [58–60] and sediment redistribution [61, 62]. The magnitude of storm-induced disturbances beyond a system's tolerance threshold can trigger an ecosystem regime shift to an alternate stable state [37,63]. For example, shifts from vegetated wetlands to mudflat and open water habitat (e.g., mangroves in Everglades National Park, USA [47,64]) drastically alter ecological function and provide reduced shoreline protection [65]. Despite their destructive power, however, storms can provide benefits to coastal habitats. Storm-induced sediment resuspension is a primary driver of vertical accretion [66,67], and net sediment import from storms can support horizontal migration and elevation maintenance [68,69]. Additionally, storm-deposited nutrients enhance primary production by stimulating root biomass and aboveground growth [70–72], facilitating vegetative resilience.

In contrast to natural systems, there are limited data available concerning the effects of storms on living shorelines. This is in part because of the relative novelty of this shoreline management approach as well as the opportunistic nature of evaluating severe weather events. Notably, the majority of these studies are confined to the mid-Atlantic coast of North America and focus on Category 1 (sustained winds of 119–153 km/h) hurricanes [34,73,74] but demonstrate that both hybrid sill-vegetation and vegetation-only living shorelines can both resist storm damage and demonstrate post-storm resilience through vegetative recovery. Living shorelines have also been shown to benefit from sediment deposited by coastal storms, much like their natural counterparts. Studies following the 2018 landfall of Hurricane Florence in North Carolina, USA, showed that hybrid living shorelines gained a mean net lateral accretion of 0.04 m, whereas natural salt marsh controls lost a mean of 0.08 m [34]. These results align with emerging evidence that accretion rates for living shorelines can outpace those of natural coastal wetlands when sediment supply is sufficient [75]. Despite such promising examples of resilience, a shift in attention to the hydrodynamic properties of hybrid vegetation-sill or breakwater living shorelines suggest that while many wave-attenuation structures effectively dissipate wave energy when emergent, some structures (e.g., Oyster Castles) may amplify wave energy under submergent conditions with higher incident wave heights—scenarios commonly encountered during major storms [76,77].

2.2. Sea-level rise

Beyond persisting through more frequent and high-magnitude storms, living shorelines must sustain their effectiveness in the face of rising sea levels. The adaptive potential of coastal habitats to sea-level rise is reflected in their ability to maintain their relative position within the coastal zone through either vertical accretion or horizontal upland migration. There is much discussion regarding the adaptive capacity of living shorelines [78,79], yet few projects have explicitly assessed the long-term vertical and horizontal migration potential of living shorelines, a critical area for further study. Gittman et al. [80] demonstrated that marsh vegetation as part of hybrid living shorelines in the southeastern United States can achieve short-term (2 yrs) elevation gains at a rate tenfold greater than local relative sea-level rise in patches below local mean sea level. Conversely, hybrid living shoreline structures can influence sediment supply to the surrounding marsh. Recent observations found unprotected salt marshes in Maryland, USA, exhibited 61 % greater sedimentation rates than marshes protected by rock sills [81].

The realized rate of sea-level rise is one of the primary factors influencing wetland migration potential, with increasing habitat losses expected for higher sea-level rise scenarios [82,83]. Beyond the rate of rising water, site and species-specific variability contribute heavily to observed adaptive capacity of coastal vegetation. Vertical accretion depends partially on tidal range, biomass production, and sedimentation rates [84–86]. In addition to annual sedimentation rates, which have the potential to be surpassed by accelerating rates of sea-level rise [87,88], independent storm events have resulted in shorelines that accrete large volumes of sediment in pulses disproportionately greater than annual rates [62], thus playing a critical role in the response of coastal wetlands and living shorelines to sea level rise.

Many reef-building species of bivalves inhabit both intertidal and subtidal zones, demonstrating resistance through a wide physiological tolerance to inundation and an ability for intertidal populations to transition to shallow subtidal habitats as sea levels rise. Despite this adaptive potential, reef-building organisms must maintain their relative position within the coastal zone to preserve their function. Dissipation of wave energy in both natural oyster reefs [89] and oyster-based living shorelines is highly dependent on water depth relative to reef crest elevation [90,91], though optimum growth range for intertidal shellfish like *Crassostrea virginica* (eastern oyster) occurs at intermediate inundation levels [92]. This presents a tradeoff where elevations that best support shoreline protection do not maximize reef productivity. As rising sea levels shift this optimum productivity zone, local factors such as nearshore sedimentation and upland topography will further influence the growth of both individual oysters and reefs, collectively [92–94]. Although limited in number, field studies have yielded promising results on the ability of *C. virginica* in the United States and *Crassostrea gigas* (Pacific oyster) in the Netherlands to keep pace with rising water, at least in high-salinity intertidal areas [95–97]. With sea-level rise increasing inundation time for intertidal bivalves, this may promote vertical accretion for higher elevation shellfish reefs.

Even if coastal habitats are capable of expanding upland at a pace consistent with sea-level rise, they will not be successful if there is no suitable upland habitat in which to move into. As such, human land use will exert significant local influence on coastal systems' response to sea-level rise. Currently, shorelines hardened with built infrastructure account for roughly 16 % of the world's coastlines [98], with a predicted 50–75 % increase across the next quarter century in highly populated coastal regions [99–101]. Even shorelines adjacent to undeveloped upland habitat can face challenges to migration if the adjacent upland's slope is too steep. Such constraints prevent the landward migration of coastal biota, resulting in "coastal squeeze", or the loss of intertidal areas against a fixed upland boundary because of rising seas [102,103].

Living shorelines on highly urbanized coasts, and those adjacent to elevated topography, will likely be some of the first to experience coastal squeeze under sea-level rise, as intertidal habitats expand upland into parks and backyards lawns, eventually abutting houses, businesses, and other infrastructure. At the point where coastal vegetation becomes level with existing human infrastructure, tidal and storm-induced flooding will have already made these areas hazardous to inhabit. Where low-lying upland does exist, however, analyses suggest that coastal wetlands could maintain or even expand their area through the conversion of upland habitat [104–106]. Living shorelines in urbanized areas are frequently modified to fit within landowner and urban environmental constraints, requiring design adjustments that can further limit their ecological function. For example, aesthetics, usability, cultural norms, and personal experiences all drive landowner priorities that affect the type and design of shoreline protection features [107,108]. Living shorelines must further navigate tradeoffs between ecological integrity and coastal protection, and the design and performance of engineered components of living shorelines will further influence their persistence under sea level rise. Coastal protection features are typically designed for specific storm return periods (e.g., 1-in-50-year events [109]) and, with growing frequency, for projected sea levels over a defined design life (expected lifespan of a structure). As sea levels rise beyond design thresholds, structures in intertidal or supratidal zones such as rock sills and oyster breakwaters will transition towards submersion, altering local hydrodynamics, reducing wave attenuation [77,110] and increasing wave overtopping [111,112]. This functional decline may undermine adjacent biotic features like intertidal vegetation, which can benefit from shoreline stabilization provided by hybrid living shoreline structures.

2.3. Changes in salinity, acidification, and temperature

Indirect effects of climate change like shifting/ fluctuating seawater properties have already begun to transform coastal and marine environments. Regional increases in precipitation-induced flooding from storms, or conversely, drought, are altering seawater salinity with marked effects on coastal biota. Oysters and mussels are particularly sensitive to rapid fluctuations in salinity [113,114], and acute salinity events have been investigated across natural shellfish reefs [57,115,116], restored reefs [117], and living shorelines [118]. The physiological stress induced from low salinity events can reduce growth and reproduction [115,119], decrease immune function [120,121], and even induce large-scale mortality on coastal biota [57,122,123]. Tolerance to environmental parameters such as salinity varies across species and populations, sometimes leading to highly localized impacts. For example, *C. virginica* grown in water with salinities in the middle of their tolerance range are better able to adapt to severe fluctuations compared to those existing at either salinity extreme [124].

Another key shift in seawater chemistry is ocean acidification, driven by rising atmospheric CO_2 levels. Global analyses show that ocean surface pH is declining around 0.02 units per decade [125], disrupting key physiological processes like shell calcification and growth in juvenile and adult gastropods [126]. Nearshore environments, in particular, are further affected by "coastal acidification", driven by riverine inputs of nitrogen and sulfur [127,128]. Although such events are often transient, repeated exposure to severe levels of acidic seawater is predicted to intensify physiological stress on coastal species [126]. Both habitat heterogeneity and facultative species interactions can enhance resistance of coastal systems in response to acidification. Field studies from the Caribbean indicate mangrove forests can act as coral refugia, promoting seawater conditions that help prevent coral bleaching [129,130]. Similarly, the presence of nearshore macrophytes can provide acidification refugia for marine calcifiers, though these effects are spatially and temporally limited [131–134].

The ocean has absorbed roughly 90 % of the atmospheric heat generated by climate change [135]. Warming winter temperatures will allow some species to expand into new regions, while others, particularly those at the equatorial edge of their distribution, may face range contraction or local extinction [136,137]. The expansion of mangrove forests into salt marsh habitats illustrates one primary example. Rising minimum temperatures have enabled mangroves to expand into previously unsuitable habitats, displacing salt marsh at temperature-controlled range limits [138,139]. While mangrove-marsh ecotone dynamics are not driven exclusively by temperature [140,141], continued warming is projected to favor mangrove dominance at many ecotonal boundaries globally [142]. Overlapping functional roles of salt marsh and mangrove vegetation may support resistance by maintaining key functions such as wave attenuation and sediment stabilization as warming temperatures shift species compositions [143–145]. However, the extent to which such functional redundancy sustains system-wide stability as community structure changes remains uncertain. This presents immediate challenges for implementing living shorelines in such regions of current and predicted future overlap. Existing research has explored comparative resilience traits (e.g., structural provisioning [146] and sediment trapping [147]) provided by mangrove and salt marsh habitats, yet there remains limited consensus on how best to adapt implementation strategies to consider species-specific tradeoffs. Research directly addressing the response of living shorelines to changes in seawater properties remains sparse. The use of natural systems as proxies provides some insights but fails to account for key differences in structure and function between natural habitats and living shorelines. For example, concrete, commonly used for wave-attenuation and oyster sill structures, may serve to chemically mitigate the effects of seawater acidification on newly settled organisms, but limited evidence suggests this buffering effect is spatially and temporally restricted [148,149].

2.4. Shifting species interactions

While physical disturbances and stressors associated with climate change continue to drive geographic and physiological changes across species, they will also indirectly affect biological community interactions and their dynamics [150,151]. Species dispersal abilities and biotic interactions combined with shifting environmental conditions will influence community assembly and reshape ecosystems processes [152–154]. As climate-driven species redistributions reshape natural ecosystems, ecological function of living shorelines may be similarly affected. Structure of biological communities is an inherent component of living shorelines, where such interventions seek to promote the natural development of biotic and abiotic coastal processes to facilitate shoreline stabilization [21]. While living shorelines leverage natural processes to stabilize coastlines, these functions depend on predictable community dynamics within a given regional context. There is a critical knowledge gap regarding how shifts in species assemblages will influence living shoreline resistance and recovery, as well as how such assemblages will vary across spatial and temporal scales.

Shifts in distributions of individual species are being observed across diverse taxa globally [155,156], causing novel species interactions that will, in turn, induce cascading effects on the structure and energy flow of biological communities [157,158]. Warming waters, for example, have enabled tropical marine species to extend their ranges poleward, reconfiguring entire communities, as evidenced from shifts in cold-temperate kelp forests across Europe, North America, and Australia to communities dominated by warm-temperate or subtropical macrophytes [159–162]. Seawater changes in temperature, acidification, and salinity may also catalyze shifts in coastal invertebrate community structure [163–166] and host-pathogen disease dynamics [167–169].

While the change in species distribution may be slow, the cumulative effects over a decadal scale could result in a very different global species composition than observed at present, with novel interspecific range overlaps [154,170] and phenological disruption resulting in large-scale ecological transformations [171]. Generalist and non-native taxa are projected to increase in abundance in many systems [172–174]. The wetland grass *Phragmites australis* (common reed) in North America, for example, can outcompete native intertidal salt marsh vegetation along highly disturbed shorelines and those with greater anthropogenic nutrient inputs [175,176]. Intrinsic biological characteristics of such introduced species result in greater tolerance of novel environmental conditions and biotic interactions [177,178]. These adaptations will likely enable non-natives to fare better under climate change than native taxa, further displacing historically dominant species and facilitating loss of biodiversity [179]. Similarly, the introduction of novel predators and pathogens is well known to disrupt population structure in marine communities. The emergence and expansion of oyster pathogen *Haplosporidium nelsoni* along the Atlantic U.S. coast in the 1950s caused mass mortality across mid-Atlantic oyster grounds before oysters developed some level of resistance over the following decade [180,181]. Existing research on marine invasions remains subjected to taxonomic bias [182], however, and the ecological consequences of these disturbances under increasing climatic stress remain poorly understood at the community scale.

Although community dynamics are predicted to shift under climate change, several mechanisms may help systems retain key functions. Species can acclimate by adjusting behavior or physiology, increasing short-term resistance at the individual and population level. Ecosystem stability can also be preserved when taxa that perform similar functions within a community exhibit diverse responses to stressors, so that declines in one species are partly offset by others with overlapping functions [183–185]. For example, in the Chesapeake Bay, USA, declines of the seagrass *Zostera marina* during warm years have been partly compensated by the expansion of heat-tolerant *Ruppia maritima*, though subtle differences in phenology and structure between the two species reveal limitations of functional redundancy in habitat provisioning [186,187]. In consequence, it is unclear how the response of individual taxa to novel species will translate to sustainability of the overall system, and to what extent resulting systems are able to preserve ecosystem functions with novel trophic networks.

2.5. Interaction of multiple stressors

The simultaneous action of multiple stressors further complicates predictions of their collective influence on coastal systems, including both natural habitats and nature-based interventions [188-190]. Coastal habitats are experiencing the fastest increase in cumulative impacts out of all marine systems, with climate change effects (i.e. sea-level rise, ocean acidification, and sea surface temperature) outpacing land-based pollution and marine stressors [191]. Site-level conditions reflect the intersection of global drivers with local stressors, including storm exposure, contaminants, and species introductions [192,193]. The integration of multiple climatic and anthropogenic stressors can lead to additive, synergistic, or antagonistic effects [194,195]. Elevated air and water temperatures, for instance, amplify negative effects of low salinity, acidification, and marine pollution on *C. virginica* [196–198]. Conversely, these same stressors can act in opposition, as illustrated by the opposing influences of moderate warming and elevated acidity on growth in bivalve families such as Pinnidae and Veneridae [199,200].

Research on the ecological consequences of multivariate stressors in coastal ecosystems has expanded over the past decade, yet significant uncertainty remains [195,201–203]. Experimental emphasis in salt marsh research has focused narrowly on stressor combinations such as CO_2 enrichment and salinity [204], and few studies address effects under realistic spatiotemporal variability despite evidence that natural dynamisms (e.g., storm-driven salinity shifts, tidal cycles, precipitation pulses) strongly mediate system responses [205,206]. For instance, in a manipulative experiment of the seagrass *Halophila ovalis*, inclusion of fluctuating stressors at high intensities led to a 36 % greater reduction in biomass compared to under constant exposure [207]. Such findings highlight the need to better represent these complex and nested dynamics in research that seeks to inform coastal management under climate change.

An equally important component of research applicability is the addition of coupled ecological components and human design choices to better represent living shorelines, which, as seen throughout this section, may diverge from that of natural systems and must be evaluated in context. Additionally, it takes time for nature-based components of restored or created habitats to develop the structural and functional characteristics typical of natural ecosystems [208] like biodiversity [209], soil organic matter [210], and topographic heterogeneity [211]. In many cases, sediment addition is a fundamental design component for coastal nature-based features, yet differences in soil texture, organic matter, and nutrient content create early constraints that influence establishment of benthic infauna, nekton, and vegetation [212–215]. Consequently, living shorelines may experience additional hurdles to resilience relative to natural coastal habitats attributed to the nature of their construction. For example, biological parameters are similar between rock sill living shorelines and natural marshes in coastal Virginia, USA, but soil organic matter, carbon, nitrogen, and phosphorus values were found to be significantly lower at living shorelines irrespective of shoreline age [188]. Such differences can promote diverging community structure that may reduce the sustainability of living shorelines compared to natural systems in response to multifaceted stressors.

2.6. Future directions

The inclusion of living shorelines in shoreline management represents a recognition of the role natural systems play in coastal protection. The increased intensity of climate effects, however, combined with continued local anthropogenic stressors like coastal development and the discharge of pollutants [216], results in an uncertain future for the protective ability of coastal features, introducing challenges for their functionality and useful lifespan. Certain cases today are thought to be inappropriate for nature-based methods, including highly developed, rapidly eroding, high-energy sites [21]. With continued coastal development, the proportion of coastline unsuitable for nature-based solutions may rise. Hard armoring techniques in these scenarios can utilize nature-based concepts by adding “green” features to increase habitat complexity. For example, innovative vegetated floating breakwaters and seawalls with enhanced texture are being incorporated into urban landscapes where full nature-based strategies are not feasible [216–219].

The contrast between adaptive natural defenses and static human infrastructure highlights a critical challenge in coastal management. While upland migration may allow wetlands to persist in certain areas, built environments cannot adapt in the same way. Roads, buildings, and other infrastructure typically remain fixed in place, creating a growing conflict between a system’s natural capacity for resilience and human habitation. More dramatic measures such as managed retreat [220,221] or rolling easements [222,223] will become necessary in some locations as hard, hybrid, and natural strategies fail to protect against more pronounced increases in floodwater and sea levels. Although such measures may become needed, the idea of relocation remains politically and socially contentious [224–226], and widespread implementation is unlikely until in-place adaptation measures fail.

The capacity of contemporary living shorelines to prevent habitat loss, storm damage, and continued erosion will be limited under more aggressive climate scenarios, particularly if they do not explicitly consider the magnitude and interactions among multiple stressors. Despite limitations of current shoreline management approaches, the expansion of knowledge concerning ecosystem responses to stressors and projected climate impacts offers a foundation to improve the utility of living shorelines as a shoreline protection strategy. We propose four overarching principles to strengthen the functionality and useful lifespan of living shorelines: Knowledge Generation, Designing for Change, Strategic Implementation, and Embracing Management (Table 2). The following sections explore actions for each principle and provide examples of how their integration into present-day living shoreline practices relate to sustainability (Table 3). Together, these principles support the persistence of diverse living shoreline types, from design and installation through adaptation and management. To illustrate how different coastal management strategies may influence shoreline function (e.g., protection, ecological structure) across time, we present a conceptual model (Fig. 3) comparing no action, hard armoring, contemporary living shoreline approaches, and future-oriented living shorelines that incorporate the four principles. Current best practices design living shorelines to be adaptive to changing conditions in the

Table 2
Principles towards future-oriented living shorelines.

Principles	Suggested Actions
Knowledge Generation (3.1)	• Optimize design & efficacy • Advance predictive capacity across multiple stressors
Designing for Change (3.2)	• Conserve or restore upland • Employ a function-first approach
Strategic Implementation (3.3)	• Apply generated knowledge • Employ regional, coordinated planning
Embracing Management (3.4)	• Incorporate strategic maintenance • Integrate adaptive interventions

Table 3
Application of principles for future-oriented living shorelines for increased sustainability.

Example	Mechanisms of Sustainability	Expected Effects
Optimize Design and Efficacy		
Experimental research to identify physiological tolerant genotypes	↑ Resistance	Enhances survival of biota under novel conditions
Advance Predictive Capacity Across Multiple Stressors		
Develop site-specific models to test shoreline performance under likely species assemblages and local stressors	↑ Resistance ↑ Recovery	Assists in site selection and design to reduce local vulnerability to stressors Enables designs that support rapid recovery and sustained function
Conserve or Restore Upland		
Regrade shoreline and create riparian buffer habitat immediately upland	↑ Recovery	Creates connectivity to suitable migration space Maintains long-term function as sea levels rise
Employ a Function-first Approach		
Increase site biodiversity through multi taxa planning for diverse fauna	↑ Recovery	Greater species functional redundancy and response diversity Prevents single point failure and buffers function
Apply Generated Knowledge		
Integrate monitoring feedback loops and adaptive project management	↑ Recovery	Corrective action enables recovery time before function loss becomes severe
Employ Regional, Coordinated Planning		
Plan living shorelines with connectivity to adjacent coastal habitat in mind	↑ Resistance ↑ Recovery	Provides habitat heterogeneity/ refugia Promotes recolonization/ recruitment
Incorporate Strategic Maintenance		
Create replacement or modular vertical augmentation pathways for hybrid structures	↑ Recovery	Enhances structure repairability and flexibility of design
Integrate Adaptive Interventions		
Plan for repeated addition of sediment (e.g., thin layer placement) to maintain shoreline elevation	↑ Resistance ↑ Recovery	Supports natural ability for vertical accretion

short-intermediate term (e.g., 20 to 50 years), improving system sustainability relative to no-action or hard-armored alternatives. Future effectiveness of living shorelines will increasingly depend on their ability to persist, function, and adapt under future climate change stressors. Although all forms of coastal defense are likely to experience declining functionality over time, the deliberate integration of the principles proposed here offers a pathway to further enhance living shoreline persistence at a higher function, as illustrated in the conceptual model.

2.7. Knowledge generation

2.7.1. Optimize design and efficacy

While existing studies provide empirical support for living shorelines, design uncertainties continue to limit their effectiveness under current and predicted future conditions [227]. Addressing these gaps through targeted knowledge generation can help enhance existing living shoreline practices (Fig. 3c) to better withstand and adapt to future conditions (Fig 3d). Decades of research in coastal engineering (e.g., [228,229]) and restoration ecology (e.g., [230,231]) provide a critical foundation for living shoreline design, but structural and functional differences between living shorelines and restored natural systems necessitate targeted investigation to advance living shoreline performance. Emerging work offers technical insights, such as optimizing wave attenuating structure configurations [232–234] or improving vegetation transplant and planting survival [235,236]. Despite these efforts, there remain significant knowledge gaps in how different materials and designs, including both biotic and abiotic living shoreline components, perform under diverse environmental conditions.

Further complicating efforts to enhance performance, the term "living shoreline" is often treated as a single intervention type, despite wide diversity in design (Fig. 1). This overgeneralization masks meaningful variation in interventions that differentially affect shoreline protection. The rapid emergence of multiple proprietary wave attenuation and artificial oyster reef products that can be used as part of a hybrid living shoreline to support existing or restored coastal features [237–239] highlights the growing complexity of design choices, each with unique financial costs, structural properties, ecological implications, and potential tradeoffs for site suitability and provisioning of ecosystem services. Comprehensive data across a wide variety of living shoreline structures are needed to understand their performance as part of living shorelines across various hydrodynamic environments.

Many properties of design, composition, material, and environmental setting have not been evaluated systematically, underscoring a need to contextualize the performance of living shorelines within such variables. Doing so can enhance understanding of how different approaches vary in resistance, recovery, and function over time, guiding more informed design and siting decisions. Tools that integrate environmental data and design criteria may help inform such decisions in the near term; for example, the Future Shorelines Model [240] which incorporates sea-level rise and location-specific parameters into shoreline suitability modeling. Similarly, the incorporation of species suitability for coastal and marine organisms offers valuable insight for anticipating ecological shifts and informing coastal protection decision-making [241, 242]. However, given the complex interplay between climate change, species dispersal, and biotic interactions; models focused solely on individual species-climate relationships remain insufficient for forecasting broader ecological trajectories [152,172].

2.7.2. Advance predictive capacity across multiple stressors

As contemporary design strategies are refined, it is equally necessary to anticipate how climate-driven changes will affect living shoreline function. This includes accounting for shifting species assemblages and altered trophic interactions that may influence the ecological integrity of living shoreline components. As illustrated in Section 2.4, these dynamics are difficult to generalize and remain poorly understood, especially in the context of multispecies interactions that underpin the performance of many nature-based strategies. Advancing the design and deployment of living shorelines under future conditions will require not only improved empirical understanding but enhanced predictive capacity. In particular, tools that integrate ecological, geomorphic, and climatic variables are needed to evaluate the persistence and function of different living shoreline approaches under a range of projected coastal futures.

Enhancing the predictive power of coastal models is critical for addressing both short-term climate stressors and guiding decadal-scale decision-making. While the field has moved beyond static representations to incorporate the dynamism of coastal environments, current models remain limited in their capacity to simulate the multi-scalar, multi-driver feedbacks that define coastal change under accelerating climate pressures [243,244]. A more comprehensive approach that incorporates multiple climate drivers; such as sea-level rise, storm-induced variability in sediment supply, increased ocean surface temperature, and changes in weather patterns; and coastal biogeomorphic parameters is needed to guide decision-support for sustainable shoreline management strategies. Additionally, the incorporation of human dimensions such as land use and policy constraints will increase the usefulness of predictive modeling as a decision-support tool. Incorporating complex climate and human dynamics into predictive models improves capacity to iteratively design living shorelines that adapt to both near-term risks and the

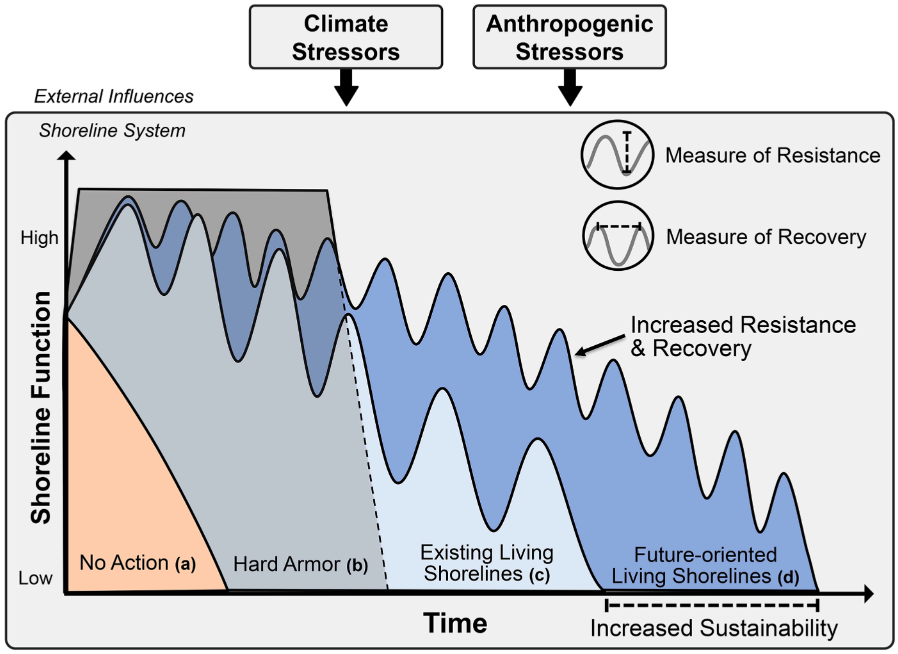

Fig. 3. Conceptual model showing shoreline function (e.g., stabilization, habitat provision) over time under four management strategies: No Action (eroding, unmanaged shorelines; (a)), Hard Armor (fully engineered shoreline; (b)), Existing Living Shorelines (present-day approaches; (c)), and Future-oriented Living Shorelines (approaches that incorporate knowledge generation, designing for change, strategic implementation, and embracing management; (d)). The graph plots the general trajectory of shoreline function across time (x axis) for all four strategies, with the y axis representing a functional threshold below which shoreline function no longer meets societal needs for coastal protection. Resistance is illustrated by the vertical distance from peak to trough, while recovery is illustrated by the horizontal distance between successive peaks. Compared to other approaches, future-oriented living shorelines exhibit higher resistance (smaller troughs) and greater recovery (shorter rebound intervals) from external influences, maintaining higher overall function over a longer period of time. Despite differences among approaches, all are expected to decline in function over time under continued climate change and anthropogenic pressures.

evolving uncertainty of climate features in the long term.

2.8. Designing for change

2.8.1. Conserve or restore upland

There has been a recent push in the field of ecological restoration to incorporate "futuristic" planning, setting forward-thinking goals based on dynamic environments rather than relying on static, historically derived target conditions [245,246]. As climate change influences dynamics between coastal societies and the natural environment, both restoration and shoreline stabilization efforts must move beyond short-term performance goals and integrate strategies that shift living shorelines towards a higher-functioning, longer-lasting trajectory of future-oriented living shorelines. One key component is designing living shorelines to accommodate future coastal change, particularly physical constraints of coastal squeeze. Sea-level rise is a critical element of climate-resilient coastal protection [78] and is increasingly incorporated into design requirements and broader shoreline management policy. Where space allows, conservation and restoration of upland habitat should be prioritized to mitigate coastal squeeze and facilitate wetland migration [247,248]. This may require reconfiguring hardened shorelines in urban watersheds, implementing landward setbacks, or incorporating migration-enabling design features in living shorelines. For example, supplementing an existing oyster sill with localized patches of bivalve substrate interspersed landward among intertidal vegetation may facilitate future horizontal reef migration and enhance reef persistence.

2.8.2. Employ a function-first approach

As coastal conditions shift, species used today in living shorelines and the techniques employed to establish them may not translate on a multidecadal timeframe. New species, whether those expanding their native range or introduced, may become dominant. Species-specific morphological and physiological traits influence shoreline protection and exhibit differential responses to environmental changes, which will in turn affect ecosystem functioning. The effectiveness of living shorelines as a future coastal protection strategy will further depend on a shift to a function-first species approach that prioritizes ecosystem functions (e.g., sediment deposition) and services (e.g., shoreline protection) over a species-specific framework aimed at maintaining historical species composition [249,250]. In areas where multiple functionally similar coastal species are expected to occur, selecting species based on service provisioning and resilience to climate stressors should be prioritized, while acknowledging that species assemblages and functions may shift as species respond to evolving environmental conditions.

In addition, rather than considering species individually, multispecies approaches that leverage interspecific interactions can buffer against adverse conditions, enhancing resistance and resilience to acute and chronic stressors. For example, mussels like *Geukensia demissa* in the United States mitigate effects of environmental stressors on *Spartina alterniflora* [251,252], and the co-restoration of these two species can increase *S. alterniflora* biomass [253]. Designing for facilitation at both the within-habitat level, as in the example above, and across-habitat levels, such as the integration of seagrass beds, shellfish reefs and mangrove plantings (i.e., habitat mosaic approach [254]) can increase sustainability under evolving environmental conditions and improve functional redundancy and response diversity within biological communities. Negative interactions such as predation can similarly benefit stability, indirectly supporting the performance of salt marsh and mangrove systems [255]. As climate change intensifies environmental stress in coastal systems, such interactions are likely to play an increasingly vital role in sustaining living shoreline function over time.

A minority of perspectives also contemplate the future role of nonnative vegetation such as *Phragmites australis* (common reed) in the United States [256,257] or *S. alterniflora* in China [258] in shoreline protection, though there is an acute need for research comparing species ability to stabilize shorelines under changing environmental conditions. Certain ecosystem services provided by nonnatives can often be lower than that provided by natives. For example, Coleman et al. [259] modeled wave attenuation by *P. australis* was up to 37 % lower than native *S. alterniflora*, likely a result of *S. alterniflora's* denser growth form. However, if established invasive or incoming range-expanding species surpass native species in regard to climate adaptation while still providing some level of equivalent functioning, or if the cost of nonnative management begins to outweigh the benefits, one must consider nontraditional future-oriented designs, including the route of promoting functional nonnative species at the potential cost of reduced biodiversity.

Finally, designing for change requires not only careful selection of species but also a function-first approach to stabilization materials. Structural living shoreline components will face heightened degradation, shifts in performance, and damage in response to climate stressors. Material choice should address not only immediate structural needs within the coastal zone but also future performance under climatic stress. For example, the acid buffering capabilities of newly set concrete with microrefugia for reef-forming species [148,149] could be important in enhancing resistance of hybrid living shoreline systems to future ocean acidification levels. When system components are chosen not only for individual performance but for how they collectively function under predicted environmental stressors, this will support progress towards future-oriented living shoreline approaches.

2.9. Strategic implementation

2.9.1. Apply generated knowledge

Equally critical to advancing living shoreline effectiveness is the widespread implementation of generated knowledge into cohesive design guidance. In practice, living shoreline design choices are shaped by multiple external factors at the project scale including cost, familiarity, aesthetics, and material availability. Moreover, knowledge exchange among practitioners, researchers, and policymakers is often disjointed [260,261], limiting the development and widespread application of best practices. While some regions have developed engineering and design guidelines (e.g., [262]) that inform implementation, the lack of globally established design-specific best practices for nature-based coastal protection techniques remains a major challenge [263].

A current gap exists between available data and the capacity to integrate the best available science into shoreline management decision-making, and there is a need to advance the use of evidence-based living shoreline design principles informed by experimental and practitioner-derived knowledge. Integrating adaptive management strategies into decision-making processes paired with greater technical assistance and support for existing tools would allow practitioners to refine techniques based on both historical performance and scientific guidance, leading to more consistent and scalable outcomes.

2.9.2. Employ regional, coordinated planning

Increasing collaboration is needed to identify research priorities that will advance the effectiveness of nature-based solutions [31,32,78]. Beyond multidisciplinary partnerships, there is also a need to shift from the current fragmented, site-specific shoreline management to cohesive and strategic, collaborative implementation using evidence-based design. While individual living shorelines address immediate erosion concerns, this patchwork approach overlooks the collective benefits of regional-scale planning such as enhancing habitat connectivity and addressing larger watershed and climate dynamics. Widespread but uncoordinated implementation of existing living shoreline approaches may improve shoreline function relative to no action or hard stabilization (Fig. 3c), but without strategic planning, their collective contribution to system-wide sustainability remains limited. Post-hoc analyses can reveal cumulative living shoreline benefits [33], but a priori, holistic coordination for nature-based shoreline management is rare. Localized shoreline suitability models have been developed (e.g., the Virginia Institute of Marine Science's Shoreline Management Model – SMM [264]), but these tools must be integrated into broader coastal governance frameworks that consider land-use planning, jurisdictional boundaries, and competing stakeholder interests.

Our analysis does not address the implications of policy (but see [265,266] for North American perspectives), but governance is likely to play a key role in the success of coastal resiliency measures at national, regional, and local levels. Effective regional-scale coordination requires mechanisms for intergovernmental collaboration, regulatory alignment, and community engagement. Without these governance structures in place, coastal regions lack the strategic efforts necessary for effective and forward-thinking shoreline management. Employing an ecosystem-based approach [267] is one mechanism to address the complex intersection of social and ecological issues inherent in coastal management. Ecosystem-based management views humans as integrated with, rather than separate from, an ecosystem and aims to balance ecological, economic, and societal objectives over appropriate spatial and temporal scales [268,269]. Applying principles of ecosystem-based planning into shoreline management under a single operational framework would allow for broader programmatic interventions that support decision-making and optimize synergies among individual projects [270].

Individual case studies highlight marine and coastal ecosystem-based management principles in operation at a regional scale [271–273], but these efforts remain piecemeal rather than driving system-wide governance reform. The lack of integration at larger scales is a key barrier to fully operationalizing ecosystem-based management in coastal management. Four major challenges to ecosystem-based management implementation across marine governance systems have been identified: existing communication gaps, governance structures, inadequate participatory processes, and institutional fragmentation [271]. These challenges are amplified in coastal systems, where the interplay between ecological dynamics, collective human actions and individual decision-making further complicate coordinated management [274].

2.10. Embracing management

2.10.1. Incorporate strategic maintenance

Conventional coastal infrastructure is built with a defined design life that accounts for material durability, wave exposure, storm return intervals, and acceptable risk level [275–277]. Offshore breakwaters, for instance, are typically designed to last 50 to 100 years, depending on site-specific conditions and level of protection required. Like any shoreline intervention, living shoreline approaches are not built to last indefinitely. The lifespan for which shoreline interventions provide desired functions varies considerably by materials used, site conditions, anticipated rates of sea-level rise, potential for wetland migration, and management goals [278,279], but well-designed living shorelines in suitable locations can be designed for 30 years or more. Even the most well-conceived living shorelines will require upkeep to remain functional [280], but the role of maintenance in extending the usability of coastal protection measures remains underdeveloped.

2.10.2. Integrate adaptive interventions

Common management actions are often initiated in response to short-term ecological (e.g., vegetation loss, emergence of non-native species) or structural (e.g., structure sinkage, dislodgment of stabilization feature) issues. In contrast, future-oriented shoreline management should be adaptive, accounting for slower, cumulative climate stressors that influence performance over decades. Maintenance needs will vary based on design choices, materials, and localized environmental conditions. For instance, a shoreline stabilized with timber cribbing may be appropriate in low energy settings but will degrade more quickly than stone or concrete, decreasing the design life, and is difficult to modify in-place beyond increasing its elevation [281]. Climate change amplifies maintenance demands and requires adaptability, but there is a lack of clear guidance for extending useful life under dynamic climate stressors. Altered storm regimes, rising sea levels, shifting seawater parameters, and changing biotic communities threaten the ecological self-maintenance that living shorelines are designed to achieve. Climate uncertainties grow substantially beyond mid-century projections [282, 283], affecting the reliability of design assumptions over more than a few decades. Adaptive interventions such as sill reinforcement, vegetation replanting, non-native species management, habitat structure supplementation, and sediment replenishment will be essential in ensuring ecological and protective function across decadal scales and will likely need to be repeated. Proactively designing with maintenance in mind can lower lifecycle costs and minimize ecological disturbance. For example, modular sill elements can simplify repairs, while planning for site access can limit ecological disruption during maintenance.

The role of management must be recognized as a core design principle essential to long-term shoreline performance. This need raises several practical questions: who is responsible for long-term maintenance? How are maintenance costs accounted for and how will these costs be funded in the future? And most importantly, how will practitioners know when intervention is needed? Integrating management into shoreline design requires explicit planning for funding, access, and repair. It also necessitates clearly defined environmental thresholds that trigger intervention, which can only be identified through monitoring. Despite widespread recognition of this need [284,285] and existing technical guidance on how to monitor living shoreline projects (e.g., [286–288]), long-term monitoring remains inconsistently implemented and rarely reintegrated into practice, compromising both the ability to make adaptive maintenance decisions and to assess the performance of climate-adaptive living shorelines. Addressing these needs will require institutional commitments that treat maintenance as a foundational design principle. The Netherlands provides one leading example through its policy of dynamic preservation, which for over three decades has mandated the ongoing nourishment of beaches and dunes [289,290] and has spurred the continued evolution of nature-based approaches throughout the region. These efforts demonstrate how upkeep can be operationalized as a foundational element in climate resilient shoreline management, offering a valuable model for how existing living shoreline approaches might evolve to increase their function and usability over time.

3. Conclusions

There exists cautious optimism in the ability of natural systems and living shorelines to provide shoreline protection for coastal communities under climate change. These systems exhibit resistance and robust recovery after storm events and have shown the potential to keep pace with rising water levels when suitable migration space and sediment supply exists. Predicting system stability becomes increasingly complex, however, when accounting for multiple interacting stressors and their indirect effects including the alteration of biotic interactions and community composition. There is significant potential to strengthen the functionality of living shorelines in response to climate change and local anthropogenic stressors. By incorporating targeted knowledge generation, designing for change, adopting strategic implementation, and embracing management, living shoreline approaches will be better equipped to persist despite future challenges. Several remaining barriers, however, limit the reliable application of future-oriented living shorelines under multiple, interacting stressors. Advancing the four principles of future-oriented living shorelines will require:

Knowledge Generation – Assessments of structural and functional differences between living shorelines, natural systems, and restored coastal systems; Evaluation of varied materials and designs performance

Designing for Change – Identification of species and assemblages best suited to provide stabilizing functions; Investigations of climate-driven shifts in biological community interactions

Strategic Implementation – Establishment of regionally relevant, evidence- and ecosystem-based practices; Development of mechanisms to translate emerging knowledge into applicable best practices

Embracing Management – Development of consistent monitoring approaches to inform adaptive management; Investigation of maintenance interventions that best preserve shoreline function

The continued protection of coastal regions will depend on the thoughtful integration of future-oriented living shorelines with spatial strategies (i.e., retreat, adaptation) and emerging innovations in green infrastructure [217,291]. Living shorelines may serve a transitional role across the next few decades or be used in tandem with other practices to delay the need for more extreme interventions by extending the lifespan of functional shoreline protection and preserving flexibility necessary for effective future adaptation measures. As an essential part of a diverse coastal management toolkit, living shoreline must evolve to meet the demands of a changing world to remain robust across future climate scenarios.

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Gabriella R. DiPetto: Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Donna Marie Bilkovic:** Writing – review & editing. **Taylor M. Sloey:** Writing – review & editing, Visualization. **Erik S. Yando:** Writing – review & editing, Visualization. **Eric L. Walters:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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