

## Review

# Nature-Based Solutions for Mediterranean Coastal Adaptation: Bridging Ecosystem Processes and Resilience Through LIFE Project Implementation

Michele Mistri \*  and Cristina Munari

Department of Chemical, Pharmaceutical and Agricultural Sciences, University of Ferrara, P.tta G. Sgarbi 1, 44121 Ferrara, Italy; cristina.munari@unife.it

\* Correspondence: michele.mistri@unife.it; Tel.: +39-0532455736

## Abstract

Nature-based Solutions (NbS) are increasingly recognised as effective approaches for enhancing coastal resilience while simultaneously supporting biodiversity, ecosystem services, and, where appropriate, climate-change mitigation. Their importance is particularly evident in the Mediterranean Basin, a climate-change hotspot exposed to sea-level rise, coastal erosion, land subsidence, sediment deficits, and intense anthropogenic pressures. This review provides a structured evidence synthesis of NbS for Mediterranean coastal adaptation, integrating ecological, hydrodynamic, geomorphological, biodiversity, governance, and implementation perspectives. We examine the principal NbS typologies, including vegetated habitats, biogenic reefs, sediment-based interventions, and hybrid approaches, with particular attention to vulnerable microtidal systems such as coastal lagoons and subsiding shorelines, including the Venice Lagoon and the Emilia-Romagna coast. Drawing on peer-reviewed literature together with evidence from European LIFE projects and restoration initiatives, the review highlights how process-based interventions can restore ecosystem functioning, strengthen coastal resilience, and provide multiple ecosystem services. At the same time, the analysis emphasises that NbS are inherently context-dependent, with their effectiveness influenced by local geomorphology, sediment availability, hydrodynamic conditions, governance capacity, and long-term management. Although important scientific uncertainties remain, wider implementation is increasingly constrained by economic, institutional, and governance barriers. The review concludes that NbS should not be regarded as stand-alone alternatives to conventional engineering, but as key components of integrated and adaptive hybrid coastal management strategies capable of supporting resilient Mediterranean coastal systems under future climate change.

Academic Editors: Guanglong Qiu, Hao Cheng, Kit Yue Kwan and Qinghua Chen

Received: 1 July 2026

Revised: 23 July 2026

Accepted: 30 July 2026

Published: 3 August 2026

**Keywords:** Nature-based Solutions; coastal adaptation; coastal resilience; climate change; ecosystem restoration; ecosystem services; hybrid coastal management; LIFE Programme; Mediterranean Sea

## 1. Introduction

Coastal environments are undergoing rapid transformation under the combined influence of climate change and anthropogenic pressures. One of the principal drivers of this transformation is global mean sea-level rise, which is projected to continue throughout the twenty-first century under all greenhouse gas emission scenarios. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, global

**Copyright:** © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

mean sea level is expected to increase by approximately 0.6–1.0 m by 2100 under high-emission pathways [1]. Rising sea levels, together with increasingly frequent and intense extreme events such as storm surges, wave extremes, and compound flooding, pose growing threats to low-lying coastal regions [1,2]. These areas are particularly vulnerable because they concentrate large populations, economic assets, and critical infrastructure, exposing them to significant environmental and socio-economic risks [3,4].

Historically, coastal protection has relied largely on hard engineering measures, including seawalls, revetments, breakwaters, and groyne systems. Although these structures provide immediate and predictable protection against specific hydrodynamic conditions, they often generate unintended environmental impacts. By altering wave dynamics and disrupting longshore sediment transport, hard defenses can intensify erosion in adjacent areas and contribute to beach narrowing and sediment deficits [5,6]. In addition, coastal armoring can degrade habitats and reduce biodiversity through coastal squeeze, a process in which intertidal ecosystems become trapped between fixed infrastructure and rising sea levels [7]. Such limitations underscore the rigidity of conventional engineering approaches and their limited capacity to accommodate dynamic and non-linear environmental change.

Against this backdrop, Nature-based Solutions (NbS) have emerged as a key framework for addressing coastal risks while enhancing ecosystem resilience. The International Union for Conservation of Nature (IUCN) defines NbS as actions that protect, sustainably manage, and restore natural or modified ecosystems in ways that address societal challenges while providing benefits for both human well-being and biodiversity [8]. The NbS concept reflects a broader shift in environmental management, where natural processes are increasingly regarded as assets capable of supporting adaptation and sustainability rather than constraints to be controlled. The European Commission has further highlighted NbS as resource-efficient, multifunctional, and adaptive interventions capable of delivering environmental, social, and economic benefits [9]. Consequently, NbS have gained increasing prominence in scientific research and policy agendas related to climate adaptation, disaster risk reduction, and ecosystem restoration [10–12].

A key advantage of NbS is their capacity to deliver multiple ecosystem services simultaneously. Unlike conventional grey infrastructure, which is generally designed to address a single function, coastal ecosystems such as wetlands, salt marshes, mangroves, dunes, and seagrass meadows provide a wide range of regulating, supporting, provisioning, and cultural ecosystem services. These include wave attenuation, shoreline stabilization, sediment retention, water-quality improvement, and biodiversity conservation, all of which contribute to enhanced coastal resilience [13,14]. In addition, many of these ecosystems support climate-change mitigation through carbon sequestration and long-term carbon storage, while sustaining socio-economic activities such as fisheries, tourism, and recreation [15–17]. Together, these ecological, protective, climatic, and socio-economic benefits make NbS an increasingly important component of integrated coastal management and climate adaptation strategies.

Nevertheless, NbS are not without limitations. Their effectiveness depends strongly on local environmental conditions, including geomorphology, hydrodynamics, sediment availability, ecological integrity, and future climate trajectories [18]. Moreover, the benefits they provide often require time to develop and may be perceived as less predictable than those offered by traditional engineering structures, reducing their appeal in decision-making processes focused on immediate risk reduction. As a result, NbS are increasingly viewed not as a universal replacement for grey infrastructure but as part of broader adaptation portfolios that may include hybrid approaches combining ecological

and engineering components [18–20].

A growing body of research has explored the application of NbS in coastal environments. Moraes et al. [21], for example, reviewed 59 case studies from European coastal and estuarine settings, documenting increasing implementation but also revealing a strong geographical concentration in the United Kingdom and the Netherlands. Most of these initiatives focused on coastal defence and were primarily based on wetland restoration and hybrid approaches. While this work provides valuable insights into the state of NbS implementation in Europe, Mediterranean coastal systems remain under-represented despite being widely recognized as climate-change hotspots characterized by high exposure to coastal hazards, intense urbanization, microtidal conditions, and limited sediment availability [22]. Furthermore, most existing reviews concentrate on specific NbS categories (e.g., wetlands, living shorelines, or ecosystem-based adaptation) or adopt broad geographical perspectives that provide limited attention to the distinctive ecological and geomorphological characteristics of Mediterranean coasts.

This review examines the role of NbS in coastal adaptation through a multi-scalar perspective, spanning global concepts and processes to their application in Mediterranean coastal environments. After outlining the main typologies of coastal NbS and the biophysical mechanisms underlying their effectiveness, the analysis focuses on the Mediterranean Basin, a region widely recognized as a climate-change hotspot characterized by high environmental vulnerability, intense human pressures, and limited adaptive capacity [22,23]. The primary objective of this review is to provide a structured evidence synthesis of NbS for Mediterranean coastal adaptation by integrating ecological, geomorphological, biodiversity, governance, and implementation perspectives within a common analytical framework. Unlike previous reviews, the present synthesis considers multiple coastal ecosystems and restoration approaches within a common process-based framework, explicitly linking ecological functioning, geomorphological dynamics, and coastal resilience. Drawing on peer-reviewed literature, LIFE projects, and other implementation-oriented case studies, the review considers NbS not merely as protective interventions but as integrated systems linking ecological, hydrodynamic, and geomorphological processes. This integrated perspective enables a comprehensive assessment of both the scientific basis and the practical implementation of NbS in Mediterranean coastal environments. Particular attention is given to transitional environments such as coastal lagoons, as well as to highly vulnerable settings affected by sea-level rise and land subsidence, including the Venice Lagoon and the Emilia-Romagna coast. This review aims to bridge the gap between scientific knowledge and practical implementation, contributing to the development of adaptive, context-specific, and scalable strategies for Mediterranean coastal resilience in a changing climate.

## 2. Methodology

This review adopted a structured evidence-synthesis approach to identify and evaluate Nature-based Solutions (NbS) applicable to Mediterranean coastal environments. The aim was not to conduct a conventional systematic review or quantitative meta-analysis, but rather to integrate peer-reviewed scientific evidence with implementation-oriented information derived from European restoration projects and technical documentation, thereby providing a comprehensive overview of NbS that have been designed, implemented, or tested in Mediterranean coastal systems.

The literature search was performed using the Web of Science Core Collection and Scopus databases and covered publications from January 1980 to January 2026. An initial exploratory search, based on broad combinations of keywords related to NbS and coastal restoration, retrieved more than 3700 records. To improve the specificity of the

evidence base and reduce the retrieval of studies outside the scope of this review, the search strategy was subsequently refined by combining the principal NbS restoration approaches with explicit geographical and functional constraints. The complete search strategy is reported in Supplementary Table S1.

The refined search yielded 138 and 86 peer-reviewed publications, respectively, which were considered sufficiently focused to allow manual assessment of their relevance. Duplicate records retrieved from the two databases were removed before manual screening of titles, abstracts, and full texts.

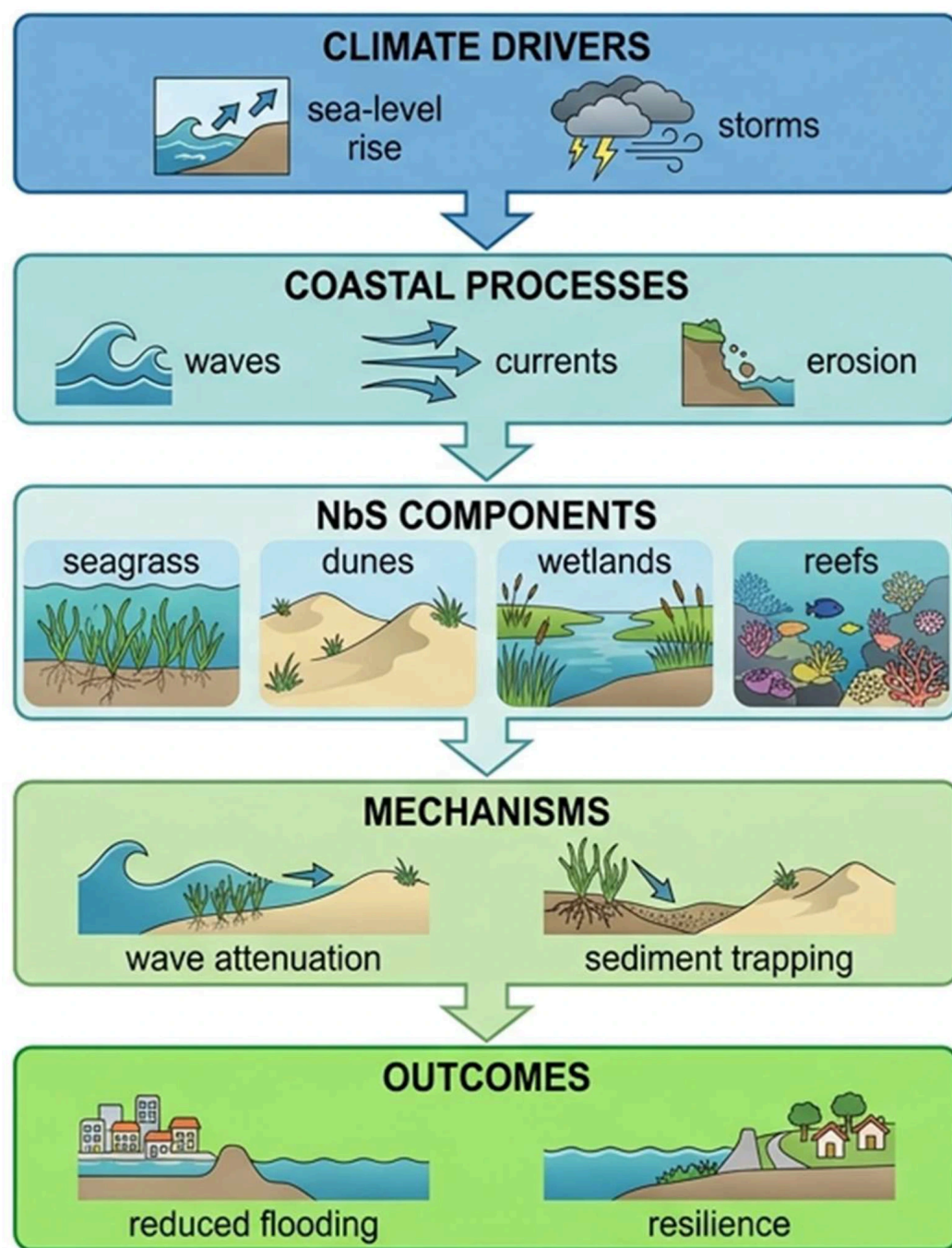
To complement the scientific literature, additional evidence was collected primarily from the European Commission LIFE Project Database and, where relevant, from official documentation associated with other EU-funded restoration initiatives. These projects were identified using the same thematic keywords adopted for the scientific literature and were included only when they described the implementation or testing of NbS within Mediterranean coastal or transitional ecosystems.

Publications and projects were included when they fulfilled the following criteria: (i) implementation or application within Mediterranean coastal or transitional environments; (ii) explicit restoration, conservation, climate adaptation, or coastal resilience objectives; (iii) sufficient technical information describing the intervention and its implementation; and (iv) documented ecological, engineering, or management outcomes. Purely conceptual studies without reference to implemented or tested restoration actions, as well as studies conducted outside Mediterranean coastal environments, were excluded.

Each intervention was subsequently classified according to the primary ecosystem targeted, restoration objective, implementation scale, and the ecosystem services expected or documented. Rather than quantitatively comparing ecological effectiveness among studies, the synthesis focused on identifying common restoration strategies, implementation constraints, transferable best practices, and current knowledge gaps across Mediterranean coastal NbS.

### **3. Global Nature-Based Solutions: Typologies, Effectiveness, and Trade-Offs**

Nature-based Solutions (NbS) for coastal protection encompass a wide range of ecosystems and restoration interventions operating across diverse climatic, ecological, and geomorphological settings [24]. Figure 1 presents a conceptual framework linking climate drivers, coastal processes, NbS components, biophysical mechanisms, and adaptation outcomes. Despite their diversity, these approaches share a common functional principle: they enhance coastal resilience by modifying hydrodynamic processes, regulating sediment dynamics, and supporting ecosystem functioning [25]. Unlike conventional grey infrastructure, which primarily reflects incoming wave energy, natural systems dissipate energy through friction, drag, and morphological adjustment, thereby reducing the forces acting on the shoreline while maintaining a greater capacity to adapt over time [26,27]. The principal categories of coastal NbS and their associated biophysical mechanisms are summarized in Table 1.



**Figure 1.** Conceptual framework illustrating the principal relationships between climate drivers, coastal processes, NbS, and ecosystem-based adaptation outcomes in coastal environments. Climate drivers, including sea-level rise and increasing storm intensity, influence coastal processes such as wave energy, hydrodynamics, and shoreline erosion. These pressures can be mitigated through different NbS components, including seagrass meadows, sand dunes, coastal wetlands, and biogenic reefs, which contribute to coastal protection through mechanisms such as wave attenuation and sediment trapping. Together, these processes enhance coastal resilience and reduce flood risk while supporting additional ecosystem services. The figure represents a conceptual synthesis of the principal mechanisms discussed in this review and is intended as an interpretative framework rather than a quantitative or predictive model. Arrows indicate generalized conceptual relationships that may vary according to local environmental conditions, ecosystem characteristics, and restoration design. The framework is based on the concepts and evidence reviewed in Refs. [8,13–18,28].

**Table 1.** Global classification and biophysical mechanisms of NbS.

| NbS Typology       | Key Species/Systems                                                | Primary Engineering Function             | Biophysical Mechanism                                                     |
|--------------------|--------------------------------------------------------------------|------------------------------------------|---------------------------------------------------------------------------|
| Vegetated Buffers  | Mangroves, Salt Marshes                                            | Wave attenuation & storm surge buffering | Increase in hydraulic roughness; root-mediated sediment binding.          |
| Biogenic Reefs     | Coral reefs, Oyster reefs, Vermetid reefs, Coralligenous platforms | Offshore wave breaking                   | Depth-induced wave breaking; topographic complexity causing turbulence.   |
| Marine Forests     | <i>Posidonia</i> , <i>Zostera</i> , <i>Cystoseira</i>              | Seabed stabilization & current reduction | Reduction of near-bed shear stress; promotion of particle settling.       |
| Soft Geomorphology | Coastal Dunes, Sand engines                                        | Sediment reservoir & flood defense       | Dynamic sediment exchange between dune and shoreface during storms.       |
| Hybrid Systems     | Bio-active seawalls, Tide pools                                    | Biodiversity enhancement & bioprotection | Micro-topography providing refugia; biocalcification protecting concrete. |

The effectiveness of NbS is closely linked to the structural complexity of the ecosystems involved [15,29]. Among the best-studied NbS are vegetated coastal habitats, including mangroves, salt marshes, and seagrass meadows [30,31]. Mangrove forests are among the most effective examples of ecosystem-based coastal defence. Their complex above- and below-ground structures can substantially reduce wave heights and storm surge impacts over relatively short distances, contributing to flood-risk reduction and shoreline stabilization [14,32]. In temperate regions, salt marshes provide similar benefits, particularly in shallow and sheltered environments where they attenuate wind-generated waves and enhance vertical sediment accretion. Their ability to trap sediments and increase surface elevation is particularly relevant under conditions of sea-level rise, provided that sediment supply and vegetation productivity remain sufficient [33].

Seagrass meadows play a complementary role by stabilizing seabed sediments and reducing erosion. By decreasing near-bed shear stress and promoting sediment deposition, they contribute to maintaining seabed elevation and water clarity [34]. These processes generate positive eco-geomorphological feedback, whereby vegetation growth enhances physical stability, which in turn supports ecosystem persistence and resilience. However, seagrass ecosystems are highly sensitive to declining water quality, increased turbidity, eutrophication, and physical disturbance, factors that may limit their long-term effectiveness in heavily modified coastal environments [35–38].

Another important category of NbS includes biogenic reef systems. Coral reefs act as natural offshore breakwaters by inducing wave breaking and dissipating large amounts of incoming wave energy before it reaches the shoreline. Global assessments have shown that coral reefs can reduce wave energy by up to 97%, making them among the most effective natural coastal defences worldwide [39]. Similarly, oyster reefs and

other shellfish-based structures can attenuate waves, stabilize sediments, improve water quality through filtration, and increase habitat complexity in estuarine and lagoonal environments [40,41]. These systems illustrate the multifunctional nature of NbS, combining coastal protection with biodiversity conservation and ecosystem-service provision.

Sediment-based interventions represent another important category of NbS. Unlike vegetated habitats and biogenic reefs, which primarily influence hydrodynamic processes, measures such as dune restoration and beach nourishment focus on restoring sediment dynamics and increasing the capacity of coastal systems to absorb and recover from disturbances [42]. Coastal dunes act as sediment reservoirs and physical barriers during storm events, reducing wave impacts and limiting inland flooding [43]. Beach nourishment can enhance shoreline stability and maintain recreational and ecological functions, although its effectiveness depends on sediment characteristics, local hydrodynamics, and long-term maintenance requirements [44].

In recent years, increasing attention has been devoted to hybrid approaches that combine natural and engineered elements. These approaches seek to combine the reliability of traditional infrastructure with the ecological benefits of NbS, particularly in densely urbanized coastal areas where space constraints often limit large-scale ecosystem restoration. Examples include living shorelines, ecologically enhanced breakwaters, textured seawalls, and bio-receptive concrete structures designed to promote habitat development while maintaining engineering performance [27]. By incorporating ecological processes into built infrastructure, hybrid solutions offer promising opportunities for enhancing both the sustainability and adaptability of coastal defence systems.

Despite their considerable potential, NbS are not universally applicable and involve important trade-offs and uncertainties. Their performance is inherently context-dependent and varies according to environmental conditions, restoration design, and temporal scale [45]. Many ecosystem-based interventions require years or even decades to reach their full protective capacity, whereas conventional engineering structures generally provide immediate levels of protection. In addition, the capacity of vegetated habitats to adapt to accelerating sea-level rise depends on factors such as sediment availability, ecological health, and space for landward migration [33]. Likewise, the effectiveness of seagrass meadows and shellfish reefs may be constrained by declining water quality, habitat fragmentation, invasive species, or changing climatic conditions [46].

Consequently, the effectiveness of NbS cannot be evaluated solely in terms of hazard reduction. Their long-term performance emerges from the interaction among ecological processes, geomorphological dynamics, ecosystem-service provision, engineering performance, and socio-economic objectives. Recognizing these interdependencies is essential for designing context-specific adaptation strategies that maximize multiple co-benefits while accounting for environmental constraints, governance requirements, and long-term management priorities.

#### **4. The Mediterranean Basin as a Climate Change Hotspot: Vulnerabilities and Ecosystem Challenges**

The Mediterranean Basin is widely recognized as one of the world's most prominent climate change hotspots, where the impacts of global warming are expected to be more pronounced than in many other regions [23,47,48]. Observational records and climate projections consistently indicate warming rates exceeding the global average, accompanied by decreasing precipitation, increasing drought frequency, rising sea-surface temperatures, and a greater occurrence of extreme events [22].

From a coastal perspective, several distinctive characteristics amplify these environmental pressures and influence the effectiveness of adaptation measures. One of the

most important is its predominantly microtidal regime, with tidal amplitudes generally below 50 cm across much of the basin [49]. Consequently, many coastal ecosystems operate within narrow hydrodynamic and elevation thresholds, making them particularly sensitive to relatively small changes in sea level. Even moderate rates of sea-level rise can alter inundation frequencies, salinity gradients, sediment transport pathways, and habitat distribution, triggering cascading consequences for ecosystem structure and functioning [33,50–52].

These climate drivers occur within a complex socio-ecological system characterized by high population density, intense coastal urbanization, extensive tourism development, and a long history of human modification [49,50]. Mediterranean shorelines support major urban centres and economic activities linked to tourism, fisheries, maritime transport, and port operations, creating intense competition for increasingly limited coastal space [49]. Over recent decades, this has resulted in widespread shoreline modification through the construction of ports, seawalls, promenades, breakwaters, and other hard-engineering structures [5,53]. Combined with rising sea levels, these historical interventions, including dredging, land reclamation, navigation-channel excavation, and infrastructure development, have altered natural sediment dynamics, reduced ecological resilience, and intensified the phenomenon of “coastal squeeze” [51,53,54]. Under these conditions, coastal habitats become trapped between fixed infrastructure and advancing waters, limiting opportunities for landward migration and increasing the risk of widespread ecosystem degradation and loss [51,54].

As a result, several Mediterranean coastal environments exhibit particularly high levels of vulnerability where the effects of sea-level rise are compounded by local land subsidence, sediment deficits, and intense cumulative human pressures [47,48,51]. Coastal lagoons, deltas, and low-lying coastal plains are especially exposed [55]. Coastal lagoons are among the most sensitive of these environments; these transitional systems are typically shallow, experience restricted water exchange, are characterized by high biological productivity, and feature strong, multi-scalar coupling between hydrodynamic, geomorphological, and ecological processes [56,57]. Because their functioning is governed by complex feedback, they are acutely responsive to variations in sea level, sediment supply, and hydrological regimes [51,56–58]. As a consequence of these anthropogenic alterations, many Mediterranean lagoon systems are already experiencing increasing rates of erosion, habitat loss, water-quality degradation, and biodiversity decline [57,59–62].

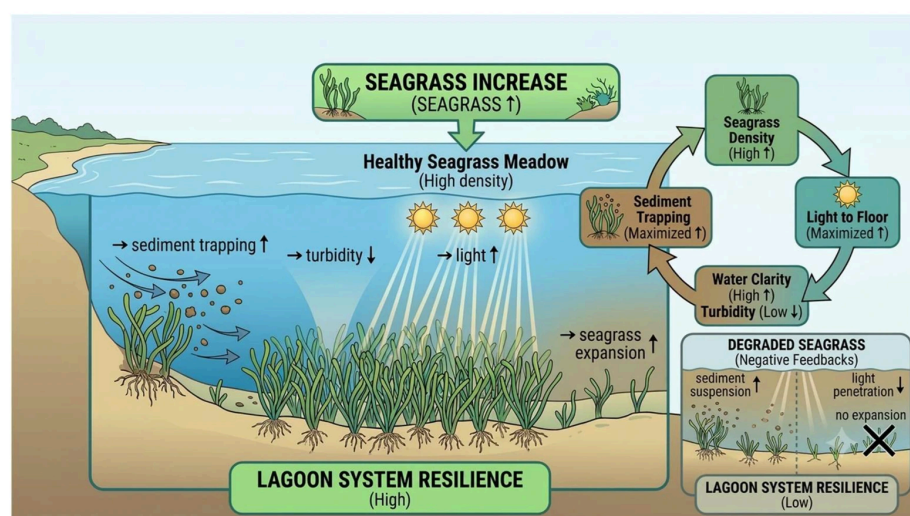
The Venice Lagoon represents one of the most extensively studied examples of these compounding challenges. In the Venice Lagoon, relative sea-level rise results from the combined effects of global sea-level increase and local land subsidence, the latter having contributed substantially to long-term elevation loss during the twentieth century [63,64]. These processes have increased both the frequency and severity of tidal flooding events, commonly known as *acqua alta* [65]. At the same time, the lagoon has undergone significant morphological changes, including the erosion of salt marshes, the widening and deepening of tidal channels, and a substantial redistribution of sediments driven by both natural and anthropogenic factors [55,66]. The progressive loss of these shallow habitats has reduced the capacity of the lagoon to attenuate waves, trap sediments, and maintain ecological functions, thereby increasing its overall vulnerability to future climate-driven impacts [13,67].

Similar pressures affect other sectors of the northern Adriatic coast, which is recognized as one of the Mediterranean sectors most exposed to the combined effects of sea-level rise and socio-economic vulnerability [47,48]. The Emilia-Romagna coastline extends for approximately 130 km along the western Adriatic Sea, is characterized by ex-

tensive sandy beaches, low-elevation backshore areas, and a high concentration of urban settlements, tourism facilities, and coastal infrastructure [68,69]. This coastal system has experienced persistent erosion over recent decades as a result of reduced sediment supply, shoreline stabilization works, and modifications to river catchments, particularly within the Po River basin [68,70]. In addition, both natural and human-induced subsidence have amplified relative sea-level rise, increasing exposure to coastal flooding and storm impacts [69,71]. Future projections suggest that these combined effects could substantially increase risks to infrastructure, agricultural land, natural habitats, and the tourism sector, which represents a key component of the regional economy [72,73].

The examples of the Venice Lagoon and the Emilia-Romagna coast illustrate a broader pattern observed across the basin: climate-change impacts are frequently amplified by long-standing anthropogenic alterations, creating cumulative pressures that exceed the adaptive capacity of natural ecosystems [47,48]. In this context, coastal vulnerability cannot be understood solely through physical indicators such as erosion rates or flood frequency, but must also consider ecological degradation, land-use change, and socio-economic exposure [74,75]. These interacting drivers highlight the need for integrated and adaptive management approaches capable of addressing both environmental and societal dimensions of coastal risk [13,14].

Despite these threats, Mediterranean coastal environments still host ecosystems of exceptional ecological and functional importance that can make significant contributions to climate adaptation and coastal resilience [13–15]. Among these, seagrass meadows dominated by *Posidonia oceanica* represent one of the region's most valuable natural assets. Endemic to the Mediterranean Sea, this species forms extensive underwater meadows that stabilize sediments, attenuate wave energy, reduce coastal erosion, improve water quality, and store substantial amounts of blue carbon [16,36,76]. Through these ecological and geomorphological functions, *P. oceanica* meadows provide multiple ecosystem services and constitute a key component of NbS [16,36,76]. Other coastal ecosystems make similarly important contributions to coastal protection. Coastal dunes act as natural sediment reservoirs and barriers against storm surges, while lagoonal wetlands and salt marshes attenuate wave energy and enhance sediment retention [13,77]. Within lagoons, vegetated habitats like seagrasses and salt marshes modify flow conditions and enhance water clarity, maintaining sediment balance and enhancing overall ecosystem resilience to external disturbances [59,60]. The main processes and feedback mechanisms underpinning NbS in lagoon environments are summarized in Figure 2.



**Figure 2.** Conceptual representation of the eco-geomorphological feedback associated with

Nature-based Solutions (NbS) in Mediterranean lagoon systems. Submerged and intertidal vegetation reduce wave energy and current velocity, promoting sediment deposition, decreasing water turbidity, and improving light availability, thereby creating positive feedback that favour vegetation persistence, expansion, and overall ecosystem resilience. External pressures, including sea-level rise and storm events, may weaken or disrupt these feedback loops, highlighting the role of NbS in enhancing the adaptive capacity of lagoon ecosystems under changing environmental conditions. The diagram synthesizes the principal ecological interactions discussed in this review and is intended as a conceptual framework rather than a quantitative model. The feedback illustrated represents generalized ecological processes whose magnitude and direction may vary according to species composition, hydrodynamic regime, sediment availability, water quality, and restoration success. The conceptual relationships are based on the evidence reviewed in Refs. [13,16,28,46,78–80].

However, the capacity of these ecosystems to continue delivering adaptation benefits is increasingly threatened by ongoing habitat fragmentation, coastal development, pollution, and sediment deficits [18]. The Mediterranean Basin therefore provides a particularly challenging yet highly informative natural laboratory for the implementation of NbS [47,48]. Understanding how NbS perform under these interacting environmental and socio-economic constraints will be essential for developing effective, scalable, and resilient adaptation strategies across the region [23,47,48]. The following section examines how these approaches have been translated into practice through restoration initiatives and adaptation projects.

## 5. Nature-Based Solutions for Mediterranean Coastal Adaptation: From Concept to Practice

The implementation of NbS in Mediterranean coastal environments requires approaches that are closely aligned with local ecological, geomorphological, and socio-economic conditions. Given the diversity of settings across the region, from lagoons and deltas to sandy beaches and highly urbanised shorelines, no single intervention can be regarded as universally applicable. Effective adaptation instead depends on selecting and, where appropriate, combining different NbS typologies within integrated, context-specific management strategies [13,14,18].

Over the past three decades, the European Union LIFE Programme has played a pivotal role in translating NbS concepts into practical restoration and adaptation measures. Since its establishment in 1992, LIFE has become one of the principal European funding instruments for ecological restoration, biodiversity conservation, and climate adaptation. Coastal and transitional ecosystems have received particular attention, especially within the Natura 2000 network, where coastal lagoons (Habitat 1150\*) are designated as priority habitats because of their ecological importance and vulnerability to environmental change. A recent synthesis identified more than 50 LIFE projects implemented in Mediterranean and Black Sea coastal lagoons, approximately half of which included direct restoration measures involving vegetation recovery, hydrological reconnection, habitat rehabilitation, or sediment management [28]. LIFE projects therefore provide an important body of implementation-oriented evidence on the feasibility, performance, constraints, and transferability of NbS in Mediterranean coastal systems.

Mediterranean NbS can be grouped into several functional categories according to the dominant ecological and physical processes involved (Table S2). These include the restoration of seagrasses and other submerged vegetation, the conservation and recovery of *Posidonia oceanica* meadows, dune and coastal-wetland restoration, the hydrological reconnection of transitional waters, and the development of biogenic and hybrid coastal structures. Although these approaches differ in their mechanisms and target environ-

ments, they share the objective of strengthening coastal adaptation through the restoration or enhancement of natural processes.

Vegetation-based NbS are among the most widely implemented approaches in Mediterranean lagoons and shallow coastal waters. Seagrass meadows stabilise sediments, reduce turbidity, improve water quality, and promote sediment deposition by decreasing near-bed shear stress [46]. In addition to these regulating functions, *P. oceanica* meadows provide substantial long-term carbon storage, support highly diverse biological communities, and contribute to shoreline stabilisation [16,78]. The conservation and restoration of seagrass habitats have consequently become central components of Mediterranean NbS strategies.

The Venice Lagoon has become an important experimental setting for testing these approaches. The LIFE SeResto project (LIFE12 NAT/IT/000331) demonstrated the feasibility of large-scale seagrass restoration through the transplantation of more than 75,000 rhizomes of submerged angiosperms, including *Zostera marina* and *Nanozostera noltii*. The intervention improved ecological status, water transparency, sediment stability, and benthic habitat quality, while promoting the natural expansion of seagrass meadows beyond the initial restoration sites [81]. Building on this experience, the LIFE TRANSFER project (LIFE19 NAT/IT/000264) extended the methodologies developed in Venice to other Mediterranean transitional environments in Italy, Greece, and Spain, thereby testing their transferability across different ecological and management contexts [38,82].

Other LIFE projects have focused on restoring the hydrological and geomorphological processes that support ecosystem functioning. The LIFE Lagoon Refresh project (LIFE16 NAT/IT/000663), for example, reintroduced freshwater from the Sile River into the Venice Lagoon, restoring salinity gradients and transitional habitats across approximately 1250 ha. By reconnecting key hydrological processes, the project increased habitat heterogeneity and improved ecological functioning at the landscape scale [83,84]. A comparable process-based perspective was adopted by LIFE MC-SALT (LIFE10 NAT/IT/000256), which promoted hydrological reconnection and habitat restoration in lagoon and saltwork systems in Italy, France, and Bulgaria. These initiatives illustrate how NbS can extend beyond individual restoration sites by addressing the processes that regulate entire coastal systems [28].

Sediment-based NbS represent another important adaptation strategy in Mediterranean environments. Coastal dunes act as dynamic sediment reservoirs that absorb storm impacts, reduce inland flooding, and maintain sediment exchanges between beaches and backshore areas [77]. Their performance depends strongly on sediment availability, vegetation cover, and sufficient space for natural morphological adjustment, all of which are frequently constrained by urbanisation and recreational pressure. Projects such as LIFE REDUNE (LIFE16 NAT/IT/000589) and LIFE CALLIOPE (LIFE17 NAT/IT/000565) demonstrate how dune restoration, habitat conservation, and visitor management can jointly support coastal protection, biodiversity recovery, and landscape resilience.

Hybrid approaches are becoming increasingly important in highly modified coastal settings where limited space or high levels of exposure constrain the feasibility of extensive ecosystem restoration. These approaches combine ecological and engineered components by incorporating natural processes into existing or newly designed infrastructure. Examples include ecologically enhanced breakwaters, textured seawalls, bioreceptive concrete structures, and restored biogenic reefs designed to attenuate wave energy while increasing habitat complexity [20,27]. Emerging initiatives such as LIFE NatuReef (LIFE22 NAT/IT/101113742) further illustrate the potential of biogenic-reef restoration in the northern Adriatic to provide both ecological benefits and physical coastal-protection

functions.

Collectively, the LIFE projects reviewed reveal a gradual transition from localised habitat restoration towards more integrated, process-based, and system-scale interventions. The strongest outcomes generally arise where habitat recovery is combined with hydrological reconnection, sediment management, long-term monitoring, and stakeholder participation, reflecting the functional interdependence of Mediterranean coastal ecosystems [13]. Nevertheless, outcomes remain strongly context-dependent. The projects differ in their target habitats, baseline ecological conditions, spatial scales, monitoring periods, and performance indicators, and no single approach can be transferred without adaptation to local conditions.

Important implementation challenges therefore remain. Many interventions are still conducted at spatial scales smaller than those at which the relevant hydrodynamic, sedimentary, and ecological processes operate, while the integration of NbS into broader coastal-planning and climate-adaptation frameworks remains incomplete [28]. Long-term monitoring is also essential to distinguish short-term restoration responses from persistent ecological and protective benefits. Addressing these limitations will be necessary to scale up successful interventions, improve their transferability, and maximise the contribution of NbS to Mediterranean coastal adaptation under changing climatic conditions.

## 6. Scaling up Nature-Based Solutions: Ecosystem Services, Economic Valuation, Governance, and Lessons Learned

### 6.1. Multifunctionality, Ecosystem-Service Provision, and the Blue Carbon Landscape

One of the principal advantages of Nature-based Solutions (NbS) is their capacity to deliver multiple ecosystem services simultaneously. Unlike conventional grey infrastructure, which is generally designed to address a single hazard, NbS can provide a broad range of ecological, social, and economic co-benefits extending well beyond coastal protection [15,17]. This multifunctionality is a major reason for their increasing integration into climate adaptation and mitigation strategies. Coastal ecosystems such as wetlands, salt marshes, dunes, seagrass meadows, and biogenic reefs contribute to wave attenuation, sediment stabilisation, shoreline protection, biodiversity conservation, and water-quality improvement [79]. To synthesise these benefits within the Mediterranean context, the ecosystem services associated with the principal NbS typologies are classified according to the Common International Classification of Ecosystem Services (CICES) framework[85] in Supplementary Table S3.

In addition to supporting coastal adaptation, many marine NbS contribute to climate-change mitigation through distinct blue-carbon pathways. However, the magnitude, persistence, and underlying mechanisms of these contributions differ substantially among habitats and should be distinguished from other ecosystem services, including biodiversity conservation, coastal protection, and water-quality regulation [12]. Coastal vegetated ecosystems sequester atmospheric carbon through primary production and store a substantial fraction of this organic matter in their sediments, where anoxic conditions slow decomposition and permit accumulation over centennial to millennial timescales [16].

Within the Mediterranean Basin, *Posidonia oceanica* meadows represent one of the largest and most persistent blue-carbon reservoirs. Their thick, fibrous mattes store considerable quantities of organic carbon while also attenuating wave energy, stabilising sediments, and supporting highly diverse benthic communities [16,78,86]. Carbon stocks may reach approximately 1500 Mg C ha<sup>-1</sup> in long-established meadows, although values vary markedly with meadow age, sediment characteristics, hydrodynamic conditions,

and local environmental history [87]. The climate-mitigation potential and broader ecosystem-service value of *P. oceanica* are therefore strongly site-dependent.

By contrast, faster-growing pioneer species such as *Zostera marina* and *Nanozostera noltii* are increasingly used in restoration programmes because of their rapid establishment and capacity to stabilise sediments during the early stages of ecosystem recovery. Their standing carbon stocks are generally lower, at approximately 40–100 Mg C ha<sup>−1</sup>, but these values likewise vary with sediment properties, hydrodynamic conditions, meadow age, and restoration status [88,89]. Rapid sediment colonisation and continued carbon burial can accelerate the recovery of degraded shallow-water environments, allowing these species to function as effective “carbon bridges” during the transition towards more mature sedimentary carbon sinks [80].

Macroalgal forests, particularly those formed by canopy-forming *Cystoseira* sensu lato, represent a different carbon pathway. Because macroalgae generally grow on rocky substrates, they contribute relatively little to local sedimentary carbon storage. Their climate-regulation role instead depends largely on the export of organic biomass, a fraction of which may be transported offshore and ultimately sequestered in deep-ocean sediments [90,91]. Mediterranean restoration initiatives such as ROCPOP-LIFE indicate that the recovery of *Cystoseira* forests can enhance primary production, habitat complexity, and ecosystem functioning while also contributing to the marine carbon cycle through biomass export.

These examples illustrate that the climate-mitigation value of marine NbS arises through distinct processes, including sedimentary carbon storage, carbon burial, and biomass export. These pathways should be evaluated separately from broader contributions to biodiversity conservation, coastal protection, and other ecosystem services.

Whereas vegetated habitats contribute to climate mitigation mainly through organic carbon sequestration and storage [92], other marine NbS support coastal adaptation primarily through structural protection. Coral reef restoration, for example, can provide highly effective natural coastal defence because reef frameworks dissipate wave energy while supporting exceptional biodiversity. However, coral calcification forms calcium carbonate through a process that releases CO<sub>2</sub> into the surrounding water:



Coral reefs should therefore not be regarded as major long-term carbon sinks, despite their important role in protecting adjacent blue-carbon habitats such as seagrass meadows and mangroves [93,94]. Their principal value as NbS lies in wave attenuation, habitat provision, biodiversity support, and the maintenance of ecosystem functioning rather than in direct climate-change mitigation.

Although true coral reefs are absent from the Mediterranean Sea, comparable structural functions are provided by ecosystem engineers such as the native European flat oyster (*Ostrea edulis*), the Pacific oyster (*Crassostrea gigas*), and the reef-forming polychaetes *Sabellaria alveolata* and *Sabellaria spinulosa* [95–97]. These organisms act as important benthic–pelagic couplers [98]. Their filtration activity can improve water clarity and facilitate the recruitment of submerged vegetation, while their complex three-dimensional structures create microrefugia, support diverse benthic assemblages, and provide nursery, feeding, and spawning habitats for numerous marine species [96–98]. Recent initiatives, including LIFE NatuReef, suggest that active biogenic-reef restoration can increase local benthic species richness while reducing wave run-up by approximately 40–80% under the site-specific hydrodynamic conditions examined [99]. The magnitude of these protective effects depends on reef morphology, water depth, incident wave climate, and storm characteristics.

Sediment-based NbS, particularly dune restoration, provide another example of multifunctionality. Restored dune systems stabilise shorelines, reduce storm impacts, and help preserve the freshwater lenses underlying many low-lying Mediterranean coastal plains [100,101]. By combining sediment nourishment with the establishment of psammophilous vegetation such as *Ammophila arenaria*, restored dunes function as dynamic sediment reservoirs that can replenish beaches after storm events while limiting saltwater intrusion into coastal aquifers [12]. These interventions consequently support both coastal protection and terrestrial biodiversity.

The quantitative values reported above reflect the environmental and experimental conditions examined in the cited studies. They should therefore be interpreted as indicative ranges rather than universally applicable thresholds.

Beyond ecosystem-service provision, different NbS can generate distinct biodiversity outcomes according to the habitat restored and the ecological processes involved. Seagrass meadows and salt marshes increase habitat complexity, enhance nursery functions, strengthen ecological connectivity, and support diverse assemblages of fish, invertebrates, and waterbirds. Dune restoration promotes the recovery of specialised psammophilous vegetation and associated arthropod communities while contributing to the conservation of priority habitats protected under the Natura 2000 network. Similarly, oyster and *Sabellaria* reefs increase habitat heterogeneity by creating complex three-dimensional structures that provide refuge, feeding areas, and spawning grounds for numerous marine organisms. Nevertheless, biodiversity responses remain strongly context-dependent and vary with environmental conditions, restoration design, baseline ecological status, and long-term management. Restoration may also involve trade-offs, including shifts in community composition or the establishment of opportunistic and non-native species, underscoring the need for adaptive management and sustained ecological monitoring.

Ultimately, ecosystem-service delivery by NbS is dynamic rather than fixed. Unlike static engineering structures, ecosystem-based interventions may become progressively more effective as ecological communities mature and eco-geomorphological feedback is re-established [13,46]. Salt marshes can adjust to moderate rates of sea-level rise through vertical sediment accretion, while seagrass meadows enhance sediment retention and water clarity. However, restoration success remains contingent on adequate sediment supply, suitable hydrodynamic conditions, sufficient water quality, and space for habitat migration. Maximising the ecological and socio-economic benefits of Mediterranean NbS therefore requires integrated planning, long-term monitoring, and adaptive management capable of balancing local stakeholder needs with wider climate-adaptation and biodiversity-conservation objectives [18,102].

## 6.2. Economic Valuation, Financing, and Governance Challenges

Despite growing evidence of their potential, the widespread implementation of NbS remains constrained by economic, financial, and institutional barriers. Conventional cost-benefit analyses often prioritise short-term, readily quantifiable outcomes, which can favour grey infrastructure because its construction costs and protective performance are more directly measured [17]. By contrast, many of the benefits delivered by NbS are distributed across multiple ecosystem services and accrue over longer time horizons, increasing the risk that they are undervalued in conventional appraisal frameworks.

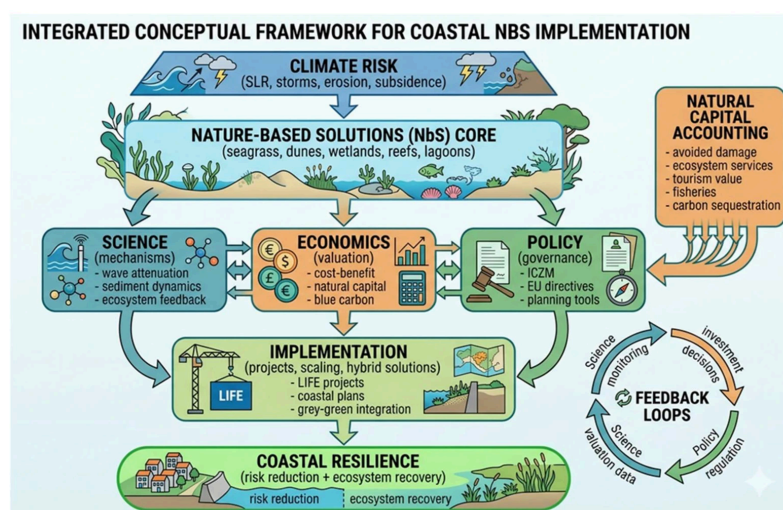
The concept of natural capital provides an important means of addressing this limitation by recognising ecosystems as assets that generate measurable benefits for society [15]. Coastal wetlands, for example, reduce flood risk through wave attenuation and storm-surge buffering, thereby functioning as natural protective infrastructure [14].

Seagrass meadows likewise contribute to climate-change mitigation through long-term carbon storage while supporting fisheries, biodiversity, and water-quality regulation [16]. Integrating these values into economic decision-making nevertheless remains difficult because of methodological uncertainty, limited standardisation among valuation approaches, and the challenge of accounting for long-term ecological change and non-market benefits.

Financing represents a further constraint. To date, NbS implementation in Europe has relied heavily on public funding, particularly through the LIFE Programme, which has played a central role in supporting innovation, pilot interventions, and proof-of-concept projects [28]. Scaling up NbS to the level required for climate adaptation will, however, require more diverse and durable financing models. Emerging options include blue-carbon finance, payments for ecosystem services, resilience-based investment mechanisms, and insurance instruments linked to demonstrated risk-reduction benefits [103]. Although promising, these approaches remain at an early stage of development, especially in Mediterranean coastal settings, where project pipelines, monitoring standards, and mechanisms for revenue generation are still limited.

Governance challenges are equally important. Coastal management across the Mediterranean is often characterised by fragmented institutional arrangements, with responsibilities distributed among multiple sectors, agencies, and administrative levels [47,51]. Such fragmentation can impede the integration of NbS into spatial planning, environmental regulation, and climate-adaptation policy. Frameworks such as Integrated Coastal Zone Management (ICZM), the Water Framework Directive (WFD), and the Marine Strategy Framework Directive (MSFD) provide important entry points for ecosystem-based approaches, but regulatory uncertainty, complex permitting procedures, limited technical guidance, and weak coordination among institutions continue to constrain implementation. Meaningful stakeholder engagement is therefore essential to improve legitimacy, reduce conflicts, and ensure that interventions reflect local socio-economic priorities and environmental conditions.

Mainstreaming NbS will require a shift from sectoral decision-making towards integrated frameworks that connect ecological processes, economic valuation, financing mechanisms, and governance arrangements. These relationships are summarised conceptually in Figure 3.



**Figure 3.** Conceptual framework illustrating the interactions among scientific knowledge, economic valuation, governance, and policy in supporting the implementation of Nature-based Solutions (NbS) in coastal systems. The framework highlights how advances in the understanding

of ecological and coastal processes, together with economic assessment (including natural capital accounting and ecosystem service valuation), can inform governance and decision-making, thereby facilitating the planning and implementation of NbS. Feedback loops linking implementation, monitoring, scientific evaluation, and policy adaptation emphasize the iterative and adaptive nature of coastal management. The diagram represents a conceptual synthesis of the enabling factors and interactions discussed throughout this review and should not be interpreted as a prescriptive or quantitative implementation model. The relationships illustrated are generalized and may vary according to governance structures, institutional capacity, socio-economic context, and environmental conditions. The framework is based on the concepts and evidence reviewed in Refs. [8,9,12,18,85,102].

### *6.3. Contrasting Implementation Pathways Across the Mediterranean Basin: Funding Mechanisms and Governance Frameworks*

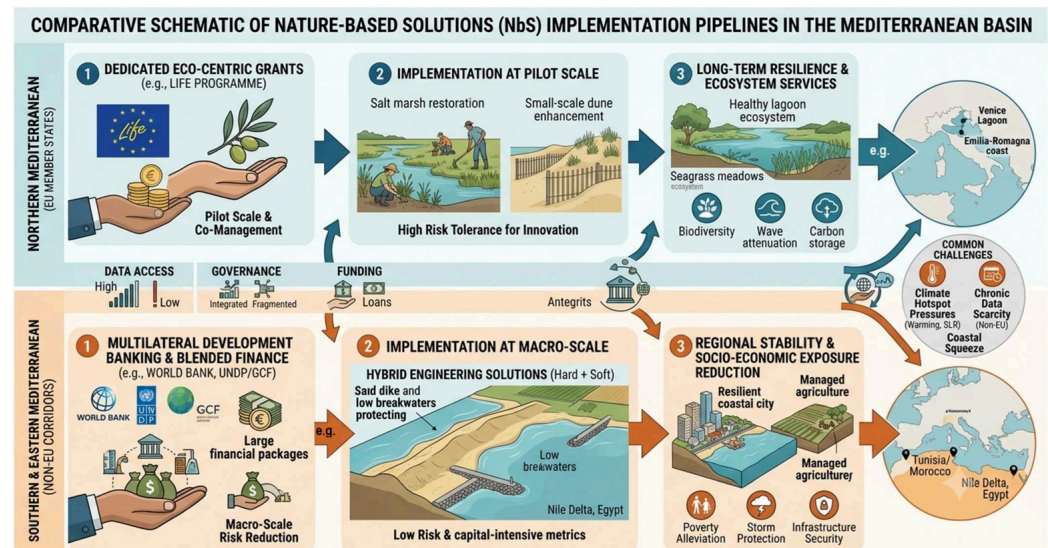
The implementation patterns discussed below represent generalized tendencies derived from the scientific literature and project documentation reviewed here. Considerable institutional, environmental, and socio-economic heterogeneity exists across Mediterranean countries, and exceptions to these broad regional patterns should therefore be anticipated.

Most well-documented, process-based NbS reported in the Western and Central Mediterranean have been implemented through the European Union's LIFE Programme and related funding mechanisms, particularly in Italy, Greece, Spain, and France. Conversely, Mediterranean countries along the southern and eastern shores, including North Africa and the Levant, remain comparatively underrepresented in the scientific literature despite experiencing some of the highest rates of coastal erosion, increasing water scarcity, and accelerating sea-level rise in the region [102].

This imbalance appears to reflect differences in governance frameworks, funding opportunities, and implementation pathways across the Mediterranean Basin [102,103]. Within EU Member States, the LIFE Programme provides dedicated financial support for pilot projects focused on ecosystem restoration, stakeholder participation, and adaptive management. These funding instruments encourage experimental approaches and facilitate the testing of innovative Nature-based Solutions under different environmental and socio-economic conditions.

In contrast, many non-EU Mediterranean countries do not have direct access to these dedicated European funding instruments. Consequently, coastal adaptation is more frequently supported through large international funding programmes led by organisations such as the World Bank, the United Nations Development Programme (UNDP), and the Green Climate Fund (GCF) [102–104]. These programmes typically pursue multiple objectives, including climate adaptation, disaster risk reduction, socio-economic development, and institutional strengthening.

As a result, project design often reflects different planning priorities (Figure 4). International development programmes typically seek solutions capable of providing measurable reductions in coastal risk while simultaneously protecting densely populated areas, strategic infrastructure, and economically important agricultural land [105]. Under these conditions, NbS are frequently integrated into broader hybrid adaptation strategies that combine ecological restoration with conventional engineering measures, rather than being implemented as standalone restoration measures.



**Figure 4.** Conceptual comparison of generalized implementation pathways for Nature-based Solutions (NbS) across the Mediterranean Basin. The upper panel illustrates the predominant implementation pathway documented in many EU Member States, where dedicated funding instruments (e.g., the EU LIFE Programme) support pilot-scale restoration projects, stakeholder participation, and ecosystem-based management. The lower panel summarizes implementation approaches commonly reported in several non-EU Mediterranean countries, where coastal adaptation is more frequently supported through international development programmes (e.g., World Bank, UNDP, and the Green Climate Fund) and often combines NbS with conventional engineering measures within hybrid adaptation strategies. The Nile Delta (Egypt) is presented as a representative example of this integrated approach. Shared regional challenges, including climate change, coastal erosion, and data limitations, influence implementation across the entire Mediterranean Basin, although governance structures, funding mechanisms, and institutional capacity differ among countries. The figure represents a conceptual synthesis of broad implementation tendencies derived from the literature and project documentation reviewed in this study and should not be interpreted as a universal classification of Mediterranean countries. The relationships illustrated are generalized and considerable environmental, institutional, and socio-economic heterogeneity exists within both the northern and southern Mediterranean regions. The framework is based on the evidence reviewed in Refs. [102–106].

A representative example of this integrated approach is the GCF-funded, UNDP-implemented project FP068, *Enhancing Climate Change Adaptation in the North Coast and Nile Delta in Egypt* [104,106]. The Nile Delta is exposed to multiple, interacting pressures, including sea-level rise, sediment deficits associated with upstream river regulation, and increasing coastal squeeze. Consequently, adaptation measures combine vegetated dune stabilisation and locally sourced sand dikes with conventional wave-breaking structures to protect agricultural land, coastal aquifers, and densely populated settlements from saltwater intrusion and coastal flooding [104,106]. Comparable implementation patterns have been reported in Morocco and Tunisia, where internationally funded coastal programmes emphasize integrated coastal zone management (ICZM), institutional capacity building, and hybrid coastal protection strategies alongside ecosystem restoration initiatives [105].

A further factor influencing NbS implementation in parts of the southern and eastern Mediterranean is the limited availability of long-term environmental datasets and monitoring programmes [102]. Compared with many EU Member States, baseline information on bathymetry, sediment dynamics, habitat distribution, and coastal processes is

often more limited, increasing uncertainty during project planning and evaluation [103]. Although this does not preclude the adoption of NbS, but it may contribute to greater reliance on hybrid or conventional engineering approaches where rapid and predictable risk reduction is required.

Bridging these regional differences will require stronger transboundary collaboration, improved knowledge exchange, and broader access to technical and financial resources. Broadening the evidence base beyond the predominantly European experience will also require adapting NbS design and implementation strategies to the diverse environmental, governance, and socio-economic contexts that characterize Mediterranean coastal systems [102].

#### *6.4. Lessons Learned and Pathways for Mainstreaming NbS*

Evidence from LIFE projects and international case studies indicates that the effectiveness of NbS depends not on isolated interventions but on the integration of ecological, hydrodynamic, and geomorphological processes. Projects such as LIFE SeResto, LIFE TRANSFER, LIFE Lagoon Refresh, and LIFE MC-SALT have demonstrated that combining vegetation restoration, hydrological reconnection, and sediment management generally produces more robust and durable outcomes than single-purpose interventions [28]. Similar conclusions emerge from global experiences, including mangrove restoration in Southeast Asia, oyster-reef restoration in North America, and large-scale sediment-management initiatives such as the Dutch Sand Motor, all illustrating the importance of working with natural processes rather than attempting to control them [14,20,44]. The Venice Lagoon provides an example of the challenges associated with balancing ecosystem-based adaptation and conventional engineering in highly vulnerable coastal systems. Alongside the NbS initiatives implemented within the lagoon, flood protection is provided by the MOSE system, a large-scale movable barrier designed to protect Venice from exceptional high-water events [107–109]. While the system plays a fundamental role in reducing flood risk, its operation temporarily modifies lagoon–sea water exchanges, highlighting the importance of carefully evaluating potential ecological trade-offs and integrating engineering solutions with ecosystem-based management. Rather than representing mutually exclusive approaches, grey infrastructure and NbS should be viewed as complementary components of hybrid adaptation strategies that seek to combine effective flood protection with the maintenance of ecosystem functioning.

Several key lessons emerge from these experiences. Although the LIFE projects reviewed target different coastal ecosystems, including seagrass meadows, coastal lagoons, salt marshes, dunes, and biogenic reefs, they share several common features. The most successful interventions consistently combined habitat restoration with hydrological or sediment management, long-term monitoring, and stakeholder engagement. At the same time, restoration outcomes varied according to local environmental conditions, implementation scale, baseline ecological status, and monitoring duration, highlighting that no single NbS approach can be universally applied across Mediterranean coastal systems. First, NbS are most effective when designed as integrated, process-based interventions that operate at the scale of the underlying coastal system. Second, long-term monitoring and adaptive management are essential to evaluate performance, support learning, and respond to changing environmental conditions. Third, successful implementation requires moving beyond site-scale restoration toward system-scale approaches that explicitly account for ecological connectivity, sediment pathways, hydrological processes, and socio-economic interactions [13,18].

Mediterranean coastal systems nevertheless present specific challenges, including

microtidal conditions, limited sediment availability, extensive urbanization, and high levels of socio-economic exposure [22,47]. Under such conditions, NbS often need to be integrated with conventional engineering measures within hybrid adaptation strategies capable of providing both ecological benefits and adequate levels of risk reduction. The long-term performance of sediment-based and hybrid NbS also depends on the engineering behaviour of the materials involved. In addition to ecological functioning, the durability of restored dunes, sand dikes, and reinforced sediment systems is controlled by factors such as sediment permeability, pore structure, cyclic wetting–drying processes, soil–vegetation interactions, and the mechanical response of granular materials under repeated hydrodynamic loading. Recent geotechnical studies have further emphasized that the durability and serviceability of hybrid coastal systems depend on the coupled effects of cyclic environmental loading, hydraulic behaviour, and soil–structure interactions [110–112]. Collectively, these factors influence erosion resistance, sediment stability, and the long-term performance of hybrid coastal interventions, emphasising the need to integrate ecological restoration with geotechnical and coastal engineering principles during both design and long-term monitoring. Consequently, NbS cannot be expected to achieve their intended ecological and engineering objectives under all environmental conditions, particularly where sediment supply is insufficient, hydrodynamic forcing exceeds ecosystem tolerance, water quality is degraded, ecological thresholds have already been crossed, or opportunities for landward habitat migration are constrained by coastal development. Under such conditions, long-term maintenance, adaptive management, and, where appropriate, hybrid solutions remain essential components of effective coastal adaptation.

Overall, the evidence reviewed in this study indicates that, although important scientific and technical challenges remain, including uncertainties related to long-term ecosystem responses, sediment availability, environmental thresholds, and future climate trajectories, the widespread implementation of NbS is increasingly constrained by economic, institutional, and governance factors. Addressing these barriers will require continued scientific research, long-term monitoring, and adaptive management, together with policy frameworks that recognise ecosystem services, support sustained financing, strengthen cross-sectoral governance, and facilitate the integration of NbS into broader coastal adaptation strategies. Advancing NbS in the Mediterranean therefore requires a transition from project-based restoration towards integrated adaptation frameworks that treat NbS not as alternatives to conventional engineering, but as essential components of hybrid, adaptive, and resilient coastal management.

## 7. Conclusions

The evidence synthesized in this review indicates that Nature-based Solutions (NbS) can represent an important component of Mediterranean coastal adaptation when appropriately designed, implemented, and managed within their environmental and socio-economic context. Across a wide range of environmental settings, NbS have demonstrated their capacity to reduce coastal risks while simultaneously supporting ecosystem functioning, biodiversity conservation, and, where appropriate, climate-change mitigation. Unlike conventional grey infrastructure, these approaches operate through the restoration and enhancement of natural processes, providing multiple ecological and socio-economic co-benefits that extend beyond hazard reduction alone.

A limitation of the present review is the heterogeneous nature of the evidence considered. In addition to peer-reviewed publications, the synthesis includes European restoration projects and institutional reports, which differ in methodological detail, monitoring duration, and reporting standards. Nevertheless, these implementation-oriented

sources provide valuable information that is often unavailable in the scientific literature and are therefore essential for developing a comprehensive understanding of NbS currently applied in Mediterranean coastal systems.

The Mediterranean Basin represents a particularly relevant setting for the application of NbS. As one of the world's most prominent climate-change hotspots, the region faces the combined pressures of sea-level rise, increasing extreme events, land subsidence, sediment deficits, and intense coastal development. At the same time, Mediterranean coastal ecosystems, including seagrass meadows, wetlands, lagoons, and dune systems, offer significant opportunities for ecosystem-based adaptation. The experiences reviewed here, particularly those supported by the LIFE Programme, demonstrate the considerable potential of NbS across a wide range of coastal environments, although restoration outcomes remain strongly influenced by local environmental conditions, implementation strategies, and long-term management.

A key lesson emerging from both Mediterranean and international experience is that the effectiveness of NbS depends on their integration within broader socio-ecological systems. The most successful interventions simultaneously address ecological, hydrodynamic, and geomorphological processes rather than focusing on individual habitats or isolated restoration actions. This evidence supports a transition from site-based restoration toward process-based, system-scale approaches that recognise the functional connectivity among coastal ecosystems.

Despite significant progress, important challenges remain. The long-term performance of NbS under accelerating climate change is still affected by uncertainties related to ecological responses, sediment availability, hydrodynamic conditions, environmental thresholds, and future climate trajectories. Furthermore, economic appraisal methods, financing mechanisms, and governance frameworks often remain poorly aligned with the multifunctional and long-term nature of ecosystem-based interventions. Continued scientific research, adaptive monitoring, and comparative evaluation of restoration outcomes will therefore remain essential, while wider implementation increasingly depends on overcoming economic, institutional, and governance barriers.

Future efforts should therefore focus on strengthening long-term monitoring, improving valuation and performance-assessment methods, and integrating NbS more effectively into coastal planning and adaptation policies. Particular attention should be devoted to hybrid approaches that combine ecological restoration with conventional engineering, especially in densely populated and highly modified coastal areas where opportunities for ecosystem migration are limited. Achieving this transition will require adaptive governance, sustained investment, and context-specific implementation strategies capable of responding to the diverse environmental and socio-economic conditions that characterise Mediterranean coastal systems.

Ultimately, NbS should not be regarded as universally applicable alternatives to conventional coastal defences, but as context-dependent components of adaptive coastal management. Their effectiveness depends on local geomorphology, sediment availability, hydrodynamic conditions, ecological integrity, governance capacity, and long-term monitoring. When appropriately integrated with conventional engineering within hybrid adaptation strategies, NbS provide a promising pathway towards more resilient and sustainable responses to climate change while preserving both the ecological integrity and the socio-economic value of Mediterranean coastal systems.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/d18080469/s1>, Table S1: Literature search strategy adopted for the structured evidence synthesis; Table S2: Comparative overview of NbS typologies applied in

European coastal environments; Table S3: Synthesis matrix of ecosystem services (ESS) provided by native coastal NbS.

**Author Contributions:** Conceptualization, methodology, investigation, writing—original draft preparation, revision M.M. & C.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** No new data were created or analyzed in this study. Data sharing is not applicable to this article.

**Acknowledgments:** The authors are grateful to the two anonymous reviewers for their thorough and constructive reviews. Their insightful comments and suggestions significantly contributed to improving the scientific quality, clarity, and balance of the manuscript. During the preparation of this manuscript, the authors used Gemini 3.6 Flash (Google AI) for assistance in generating and optimizing Figures 1–4. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

NbS

Nature-based Solutions

## References

1. IPCC. Sections. In *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Lee, H., Romero, J., Eds.; IPCC: Geneva, Switzerland, 2023; pp. 35–115. [Google Scholar] [CrossRef]
2. Oppenheimer, M.; Glavovic, B.C.; Hinkel, J.; van de Wal, R.; Magnan, A.K.; Abd-Elgawad, A.; Cai, R.; Cifuentes-Jara, M.; DeConto, R.M.; Ghosh, T.; et al. Sea level rise and implications for low-lying islands, coasts and communities. In *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*; Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegria, A., Nicolai, M., Okem, A., Eds.; Intergovernmental Panel on Climate Change (IPCC): Geneva, Switzerland, 2019; pp. 321–445. [Google Scholar]
3. Hinkel, J.; Lincke, D.; Vafeidis, A.T.; Perrette, M.; Nicholls, R.J.; Tol, R.S.J.; Marzeion, B.; Fettweis, X.; Ionescu, C.; Levermann, A. Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 3292–3297. [Google Scholar] [CrossRef]
4. Neumann, B.; Vafeidis, A.T.; Zimmermann, J.; Nicholls, R.J. Future coastal population growth and exposure to sea-level rise and coastal flooding: A global assessment. *PLoS ONE* **2015**, *10*, e0131375. [Google Scholar] [CrossRef]
5. Bulleri, F.; Chapman, M.G. The introduction of coastal infrastructure as a driver of change in marine environments. *J. Appl. Ecol.* **2010**, *47*, 26–35. [Google Scholar] [CrossRef]
6. Dugan, J.E.; Airoidi, L.; Chapman, M.G.; Walker, S.J.; Schlacher, T. Estuarine and coastal structures: Environmental effects, a focus on shore and nearshore structures. In *Treatise on Estuarine and Coastal Science*; Wolanski, E., McLusky, D., Eds.; Academic Press: London, UK, 2012; pp. 17–41. [Google Scholar] [CrossRef]
7. Heery, E.C.; Bishop, M.J.; Critchley, L.P.; Bugnot, A.B.; Airoidi, L.; Mayer-Pinto, M.; Sheehan, E.V.; Coleman, R.A.; Loke, L.H.L.; Johnston, E.L.; et al. Identifying the consequences of ocean sprawl for sedimentary habitats. *J. Exp. Mar. Biol. Ecol.* **2017**, *492*, 31–48. [Google Scholar] [CrossRef]
8. Cohen-Shacham, E.; Walters, G.; Janzen, C.; Maginnis, S. (Eds.) *Nature-Based Solutions to Address Global Societal Challenges*; IUCN: Gland, Switzerland, 2016; pp. 1–97. [CrossRef]
9. European Commission. *Nature-Based Solutions: State of the Art in EU-Funded Projects*; Wild, T., Freitas, T., Vandewoestijne, S., Eds.; Publications Office of the European Union: Luxembourg, 2020. [Google Scholar] [CrossRef]

10. Eggermont, H.; Balian, E.; Azevedo, J.M.N.; Beumer, V.; Brodin, T.; Claudet, J.; Fady, B.; Grube, M.; Keune, H.; Lamarque, P.; et al. Nature-based solutions: New influence for environmental management and research in Europe. *GAIA* **2015**, *24*, 243–248. [Google Scholar] [CrossRef]
11. Nesshöver, C.; Assmuth, T.; Irvine, K.N.; Rusch, G.M.; Waylen, K.A.; Delbaere, B.; Haase, D.; Jones-Walters, L.; Keune, H.; Kovacs, E.; et al. The science, policy and practice of nature-based solutions: An interdisciplinary perspective. *Sci. Total Environ.* **2017**, *579*, 1215–1227. [Google Scholar] [CrossRef] [PubMed]
12. IUCN. *Global Standard for Nature-Based Solutions. A User-Friendly Framework for the Verification, Design and Scaling Up of NbS*; IUCN: Gland, Switzerland, 2020. [Google Scholar] [CrossRef]
13. Temmerman, S.; Meire, P.; Bouma, T.J.; Herman, P.M.; Ysebaert, T.; De Vriend, H.J. Ecosystem-based coastal defence in the face of global change. *Nature* **2013**, *504*, 79–83. [Google Scholar] [CrossRef] [PubMed]
14. Narayan, S.; Beck, M.W.; Reguero, B.G.; Losada, I.J.; van Wesenbeeck, B.; Pontee, N.; Sanchirico, J.N.; Ingram, J.C.; Lange, G.M.; Burks-Copes, K.A. The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences. *PLoS ONE* **2016**, *11*, e0154735. [Google Scholar] [CrossRef] [PubMed]
15. Barbier, E.B.; Hacker, S.D.; Kennedy, C.; Koch, E.W.; Stier, A.C.; Silliman, B.R. The value of estuarine and coastal ecosystem services. *Ecol. Monogr.* **2011**, *81*, 169–193. [Google Scholar] [CrossRef]
16. Duarte, C.M.; Losada, I.J.; Hendriks, I.E.; Mazarrasa, I.; Marbà, N. The role of coastal plant communities for climate change mitigation and adaptation. *Nat. Clim. Change* **2013**, *3*, 961–968. [Google Scholar] [CrossRef]
17. Seddon, N.; Chausson, A.; Berry, P.; Girardin, C.A.J.; Smith, A.; Turner, B. Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philos. Trans. R. Soc. B Biol. Sci.* **2020**, *375*, 20190120. [Google Scholar] [CrossRef] [PubMed]
18. Bridges, T.S.; Smith, J.M.; King, J.K.; Simm, J.D.; Dillard, M.; deVries, J.; Reed, D.; Piercy, C.D.; van Zanten, B.; Arkema, K.; et al. Coastal Natural and Nature-Based Features: International Guidelines for Flood Risk Management. *Front. Built Environ.* **2022**, *8*, 904483. [Google Scholar] [CrossRef]
19. van Wesenbeeck, B.K.; de Boer, W.; Narayan, S.; van der Star, W.R.L.; de Vries, M.B. Coastal and riverine ecosystems as adaptive flood defenses under a changing climate. *Mitig. Adapt. Strateg. Glob. Change* **2017**, *22*, 1087–1094. [Google Scholar] [CrossRef]
20. Morris, R.L.; Konlechner, T.M.; Ghisalberti, M.; Swearer, S.E. From grey to green: Efficacy of eco-engineering solutions for nature-based coastal defence. *Glob. Change Biol.* **2018**, *24*, 1827–1842. [Google Scholar] [CrossRef] [PubMed]
21. Moraes, R.P.L.; Reguero, B.G.; Mazarrasa, I.; Ricker, M.; Juanes, J.A. Nature-Based Solutions in Coastal and Estuarine Areas of Europe. *Front. Environ. Sci.* **2022**, *10*, 829526. [Google Scholar] [CrossRef]
22. Lionello, P.; Scarascia, L. The relation between climate change in the Mediterranean region and global warming. *Reg. Environ. Change* **2018**, *18*, 1481–1493. [Google Scholar] [CrossRef]
23. Cramer, W.; Guiot, J.; Fader, M.; Garrabou, J.; Gattuso, J.P.; Iglesias, A.; Lange, M.A.; Lionello, P.; Llasat, M.C.; Mourou, M.; et al. Climate change and interconnected risks to sustainable development in the Mediterranean. *Nat. Clim. Change* **2018**, *8*, 972–980. [Google Scholar] [CrossRef]
24. Slinger, J.; Stive, M.; Luijendijk, A. Nature-Based Solutions for Coastal Engineering and Management. *Water* **2021**, *13*, 976. [Google Scholar] [CrossRef]
25. Maldonado, S.; Antolinez, J.A.A.; Dodd, N.; Silva, R. Editorial: Prediction of coastal morphological evolution in the context of climate change adaptation and nature-based engineering. *Front. Mar. Sci.* **2026**, *12*, 1766414. [Google Scholar] [CrossRef]
26. Denny, M. Wave-energy dissipation: Seaweeds and marine plants are ecosystem engineers. *Fluids* **2021**, *6*, 151. [Google Scholar] [CrossRef]
27. Perricone, V.; Mutalipassi, M.; Mele, A.; Buono, M.; Vicinanza, D.; Contestabile, P. Nature-based and bioinspired solutions for coastal protection: An overview among key ecosystems and a promising pathway for new functional and sustainable designs. *ICES J. Mar. Sci.* **2023**, *80*, 1218–1239. [Google Scholar] [CrossRef]
28. De Wit, R.; Boutin, N. European LIFE Projects Dedicated to Ecological Restoration in Mediterranean and Black Sea Coastal Lagoons. *Environments* **2023**, *10*, 101. [Google Scholar] [CrossRef]
29. Rao, N.; Ghermandi, A.; Portela, R.; Wang, X. Global values of coastal ecosystem services: A spatial economic analysis of shore-line protection values. *Ecosyst. Serv.* **2015**, *11*, 95–105. [Google Scholar] [CrossRef]
30. Fu, H. A comprehensive review of nature-based solutions: Current status and future research. *AIMS Environ. Sci.* **2023**, *10*, 677–690. [Google Scholar] [CrossRef]

31. Ondiviela, B.; Losada, I.J.; Lara, J.L.; Maza, M.; Galván, C.; Bouma, T.J.; van Belzen, J. The role of seagrasses in coastal protection in a changing climate. *Coast. Eng.* **2014**, *87*, 158–168. [Google Scholar] [CrossRef]
32. Mazda, Y.; Magi, M.; Ikeda, Y.; Kurokawa, T.; Asano, T. Wave reduction in a mangrove forest dominated by *Sonneratia* sp. *Wetl. Ecol. Manag.* **2006**, *14*, 365–378. [Google Scholar] [CrossRef]
33. Kirwan, M.L.; Megonigal, J.P. Tidal wetland stability in the face of human impacts and sea-level rise. *Nature* **2013**, *504*, 53–60. [Google Scholar] [CrossRef] [PubMed]
34. Leonardi, N.; Ganju, N.K.; Fagherazzi, S. A linear relationship between wave power and erosion determines salt-marsh resilience to violent storms and hurricanes. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 64–68. [Google Scholar] [CrossRef] [PubMed]
35. Sfriso, A. Temporal and spatial responses of *Ulva rigida* C. Ag. growth to environmental and tissue concentrations of nutrients in the lagoon of Venice. *Bot. Mar.* **1995**, *38*, 557–573. [Google Scholar] [CrossRef]
36. Boudouresque, C.F.; Bernard, G.; Pergent, G.; Abdesslem Shili, A.; Verlaque, M. Regression of Mediterranean seagrasses caused by natural processes and anthropogenic disturbances and stress: A critical review. *Bot. Mar.* **2009**, *52*, 395–418. [Google Scholar] [CrossRef]
37. Munari, C.; Casoni, E.; Cozzula, C.; Pasculli, A.; Pezzi, M.; Sciuto, K.; Sfriso, A.A.; Sfriso, A.; Mistri, M. The Ecological Role of *Ruppia cirrhosa* (Petagna) Grande in a Choked Lagoon. *Water* **2023**, *15*, 2162. [Google Scholar] [CrossRef]
38. Sfriso, A.; Buosi, A.; Silan, G.; Mistri, M.; Munari, C.; Sfriso, A.A. Macrophytes and Phytoplankton, Two Primary Antithetical Producers in Degraded Water Systems. *Water* **2025**, *17*, 338. [Google Scholar] [CrossRef]
39. Beck, M.W.; Losada, I.J.; Menéndez, P.; Reguero, B.G.; Díaz-Simal, P.; Fernández, F. The global flood protection savings provided by coral reefs. *Nat. Commun.* **2018**, *9*, 2186. [Google Scholar] [CrossRef] [PubMed]
40. Cressman, K.; Posey, M.H.; Mallin, M.A.; Leonard, L.A.; Alphin, T.D. Effects of oyster reefs on water quality in a tidal creek estuary. *J. Shellfish Res.* **2003**, *22*, 753–762. [Google Scholar]
41. Hong, X.; Ji, Y.; Yan, J.; Cheng, J.; Wu, S.; Li, Q. Study on the Wave-Dissipation Effect of Oyster Reefs Based on the SWAN Numerical Model. *Water* **2023**, *15*, 2884. [Google Scholar] [CrossRef]
42. van der Meulen, F.; Ijff, S.; van Zetten, R. Nature-based solutions for coastal adaptation management, concepts and scope, an overview. *Nord. J. Bot.* **2023**, *2023*, e03290. [Google Scholar] [CrossRef]
43. Sedrati, M.; Dalour, L.; Bulot, G.; Metge, N. Nature-based solutions for coastal dune restoration: The case study of AlgoBox in South Brittany, France. *Ecol. Eng.* **2025**, *210*, 107440. [Google Scholar] [CrossRef]
44. Stive, M.J.F.; de Schipper, M.A.; Luijendijk, A.P.; Aarninkhof, S.G.J.; van Gelder-Maas, C.; van Thiel de Vries, J.S.M.; de Vries, S.; Henriquez, M.; Marx, S.; Ranasinghe, R.W.M.R.J.B. A new alternative to saving our beaches from sea-level rise: The sand engine. *J. Coast. Res.* **2013**, *29*, 1001–1008. [Google Scholar] [CrossRef]
45. Chairat, S.; Gheewala, S.H. The conceptual quantitative assessment framework for nature-based solutions (NbS). *Nat.-Based Solut.* **2024**, *6*, 100152. [Google Scholar] [CrossRef]
46. Leonardi, N. A review of seagrass contributions to regulating services of sediment stability, carbon sequestration and coastal energy attenuation. *Ecol. Eng.* **2026**, *227*, 107949. [Google Scholar] [CrossRef]
47. MedECC. *Climate and Environmental Change in the Mediterranean Basin—Current Situation and Risks for the Future: First Mediterranean Assessment Report*; Cramer, W., Guiot, J., Marini, K., Eds.; Union for the Mediterranean, Plan Bleu, UNEP/MAP: Marseille, France, 2020; 632p. Available online: <https://www.medecc.org/first-mediterranean-assessment-report/> (accessed on 24 June 2026). [Google Scholar]
48. IPCC. *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2022. [Google Scholar] [CrossRef]
49. Di Carlo, G.; Otero, M.M. *A Changing Mediterranean Coastal Marine Environment under Predicted Climate-Change Scenarios*; IUCN: Gland, Switzerland; Malaga, Spain, 2012. [Google Scholar]
50. Arranz, I.; Batllori, E.; Linares, C.; Ripple, W.J.; Bonada, N. Integrative research of Mediterranean climate regions: A global call to action. *Environ. Conserv.* **2024**, *51*, 71–78. [Google Scholar] [CrossRef]
51. Nicholls, R.J.; Cazenave, A. Sea-level rise and its impact on coastal zones. *Science* **2010**, *328*, 1517–1520. [Google Scholar] [CrossRef] [PubMed]
52. Fagherazzi, S.; Mariotti, G.; Leonardi, N.; Canestrelli, A.; Nardin, W.; Kearney, W.S. Salt marsh dynamics in a period of accelerated sea level rise. *J. Geophys. Res. Earth Surf.* **2020**, *125*, e2019JF005200. [Google Scholar] [CrossRef]

53. Airoidi, L.; Beck, M.W. Loss, status and trends for coastal marine habitats of Europe. *Oceanogr. Mar. Biol. Annu. Rev.* **2007**, *45*, 345–405. [Google Scholar] [CrossRef]
54. Doody, J.P. Coastal Squeeze and Managed Realignment in Southeast England, Does it Tell Us Anything about the Future? *Ocean Coast. Manag.* **2013**, *79*, 34–41. [Google Scholar] [CrossRef]
55. Day, J.W.; Pont, D.; Hensel, P.F.; Ibáñez, C. Impacts of sea-level rise on deltas in the Gulf of Mexico and the Mediterranean: The importance of pulsing events to sustainability. *Estuaries* **1995**, *18*, 636–647. [Google Scholar] [CrossRef]
56. Kjerfve, B. *Coastal Lagoon Processes*; Elsevier Oceanography Series; Elsevier: Amsterdam, The Netherlands, 1994; Volume 60. [Google Scholar]
57. Pérez-Ruzafa, A.; Campillo, S.; Fernández-Palacios, J.M.; García-Lacunza, A.; García-Oliva, M.; Ibáñez, H.; Navarro-Martínez, P.C.; Pérez-Marcos, M.; Pérez-Ruzafa, I.M.; Quispe-Becerra, J.I.; et al. Long-Term Dynamic in Nutrients, Chlorophyll a, and Water Quality Parameters in a Coastal Lagoon During a Process of Eutrophication for Decades, a Sudden Break and a Relatively Rapid Recovery. *Front. Mar. Sci.* **2019**, *6*, 26. [Google Scholar] [CrossRef]
58. Lotze, H.K.; Lenihan, H.S.; Bourque, B.J.; Bradbury, R.H.; Cooke, R.G.; Kay, M.C.; Kidwell, S.M.; Kirby, M.X.; Peterson, C.H.; Jackson, J.B. Depletion, degradation, and recovery potential of estuaries and coastal seas. *Science* **2006**, *312*, 1806–1809. [Google Scholar]
59. Viaroli, P.; Bartoli, M.; Giordani, G.; Naldi, M.; Orfanidis, S.; Zaldivar, J.M. Community shifts, alternative stable states, biogeochemical controls and feedbacks in eutrophic coastal lagoons: A brief overview. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **2008**, *18*, S105–S117. [Google Scholar] [CrossRef]
60. Viaroli, P.; Christian, R.R. Description of trophic status, hyperautotrophy and dystrophy of a coastal lagoon through a potential oxygen production and consumption index—TOSI: Trophic Oxygen Status Index. *Ecol. Indic.* **2004**, *3*, 237–250. [Google Scholar] [CrossRef]
61. Newton, A.; Icely, J.; Cristina, S.; Perillo, G.M.E.; Turner, R.E.; Ashan, D.; Cragg, S.; Luo, Y.; Tu, C.; Li, Y.; et al. Anthropogenic, Direct Pressures on Coastal Wetlands. *Front. Ecol. Evol.* **2020**, *8*, 144. [Google Scholar] [CrossRef]
62. Mistri, M.; Newton, A.; Pérez-Ruzafa, A.; Reizopoulou, S. *Ecosystem Services, Biodiversity and Water Quality in Transitional Ecosystems*; Frontiers Media SA: Lausanne, Switzerland, 2023. [Google Scholar] [CrossRef]
63. Carbognin, L.; Teatini, P.; Tosi, L. Eustacy and land subsidence in the Venice Lagoon at the beginning of the new millennium. *J. Mar. Syst.* **2004**, *51*, 345–353. [Google Scholar] [CrossRef]
64. Zanchettin, D.; Bruni, S.; Raich, F.; Lionello, P.; Adloff, F.; Androsov, A.; Antonioli, F.; Artale, V.; Carminati, E.; Ferrarin, C.; et al. Sea-level rise in Venice: Historic and future trends. *Nat. Hazards Earth Syst. Sci.* **2021**, *21*, 2643–2678. [Google Scholar] [CrossRef]
65. Ferrarin, C.; Ghezzi, M.; Umgiesser, G.; Tagliapietra, D.; Camatti, E.; Zaggia, L.; Sarretta, A. Assessing hydrological effects of human interventions on coastal systems: Numerical applications to the Venice Lagoon. *Hydrol. Earth Syst. Sci.* **2013**, *17*, 1733–1748. [Google Scholar] [CrossRef]
66. Carniello, L.; Defina, A.; D’Alpaos, L. Morphological evolution of the Venice lagoon: Evidence from the past and trend for the future. *J. Geophys. Res.* **2009**, *114*, F04002. [Google Scholar] [CrossRef]
67. Möller, I.; Kudella, M.; Rupprecht, F.; Spencer, T.; Paul, M.; Van Wesenbeeck, B.K.; Wolters, G.; Jensen, K.; Bouma, T.J.; Miranda-Lange, M.; et al. Wave attenuation over coastal salt marshes under storm surge conditions. *Nat. Geosci.* **2014**, *7*, 727–731. [Google Scholar] [CrossRef]
68. Perini, L.; Calabrese, L.; Salerno, G.; Ciavola, P.; Armaroli, C. Evaluation of coastal vulnerability to flooding: Comparison of two different methodologies adopted by the Emilia-Romagna region (Italy). *Nat. Hazards Earth Syst. Sci.* **2016**, *16*, 181–194. [Google Scholar] [CrossRef]
69. Armaroli, C.; Duo, E.; Viavattene, C. From Hazard to Consequences: Evaluation of Direct and Indirect Impacts of Flooding Along the Emilia-Romagna Coastline, Italy. *Front. Earth Sci.* **2019**, *7*, 203. [Google Scholar] [CrossRef]
70. Syvitski, J.; Kettner, A.; Overeem, I.; Jia, Y.; Cohen, S.; Brakenridge, G.R.; Day, J.W.; Vörösmarty, C.; Saito, Y.; Giosan, L.; et al. Sinking deltas due to human activities. *Nat. Geosci.* **2009**, *2*, 681–686. [Google Scholar] [CrossRef]
71. Teatini, P.; Tosi, L.; Strozzi, T.; Carbognin, L.; Wegmüller, U.; Rizzetto, F. Mapping regional land displacements in the Venice coastland by an integrated monitoring system. *Remote Sens. Environ.* **2005**, *98*, 403–413. [Google Scholar] [CrossRef]
72. Armaroli, C.; Ciavola, P.; Perini, L.; Calabrese, L.; Lorito, S.; Valentini, A.; Masina, M. Critical storm thresholds for significant morphological changes and damage along the Emilia-Romagna coastline, Italy. *Geomorphology* **2012**, *143–144*, 34–51. [Google Scholar] [CrossRef]

73. Vousdoukas, M.I.; Mentaschi, L.; Hinkel, J.; Ward, P.J.; Mongelli, I.; Ciscar, J.C.; Feyen, L. Economic motivation for raising coastal flood defenses in Europe. *Nat. Commun.* **2020**, *11*, 2119. [Google Scholar] [CrossRef] [PubMed]
74. Nicholls, R.J.; Wong, P.P.; Burkett, V.R.; Codignotto, J.O.; Hay, J.E.; McLean, R.F.; Ragoonaden, S.; Woodroffe, C.D. Coastal systems and low-lying areas. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E., Eds.; Cambridge University Press: Cambridge, UK, 2007; pp. 315–356. [Google Scholar]
75. Wong, P.P.; Losada, I.J.; Gattuso, J.-P.; Hinkel, J.; Khattabi, A.; McInnes, K.L.; Saito, Y.; Sallenger, A. Coastal systems and low-lying areas. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014; pp. 361–409. [Google Scholar]
76. Telesca, L.; Belluscio, A.; Criscoli, A.; Ardizzone, G.; Apostolaki, E.T.; Fraschetti, S.; Gristina, M.; Knittweis, L.; Martin, C.S.; Pergent, G.; et al. Seagrass meadows (*Posidonia oceanica*) distribution and trajectories of change. *Sci. Rep.* **2015**, *5*, 12505. [Google Scholar] [CrossRef] [PubMed]
77. Feagin, R.A.; Irish, J.L.; Möller, I.; Williams, A.M.; Colón-Rivera, R.J.; Mousavi, M.E. Engineering properties of wetland plants with application to wave attenuation. *Coast. Eng.* **2011**, *58*, 251–255. [Google Scholar] [CrossRef]
78. Campagne, C.S.; Salles, J.-M.; Boissery, P.; Deter, J. The seagrass *Posidonia oceanica*: Ecosystem services identification and economic evaluation of goods and benefits. *Mar. Pollut. Bull.* **2015**, *97*, 391–400. [Google Scholar] [CrossRef] [PubMed]
79. Jordan, P.; Fröhle, P. Bridging the gap between coastal engineering and nature conservation? *J. Coast. Conserv.* **2022**, *26*, 4. [Google Scholar] [CrossRef]
80. Sfriso, A.A.; Juhmani, A.-S.; Tomio, Y.; Wedyan, M.; Buosi, A.; Galamini, G.; Pignoni, E.; Ferretti, G.; Cunsolo, F.; Forlani, G.; et al. Boosting blue carbon via seagrass restoration: Decadal insights from *Nanozostera noltei* and *Ruppia cirrhosa*. *Sci. Total Environ.* **2026**, *1013*, 181267. [Google Scholar] [CrossRef] [PubMed]
81. Sfriso, A.; Buosi, A.; Facca, C.; Sfriso, A.A.; Tomio, Y.; Juhmani, A.-S.; Wolf, M.A.; Franzoi, P.; Scapin, L.; Ponis, E.; et al. Environmental restoration by aquatic angiosperm transplants in transitional water systems: The Venice Lagoon as a case study. *Sci. Total Environ.* **2021**, *795*, 148859. [Google Scholar] [CrossRef] [PubMed]
82. Mistri, M.; Albéri, M.; Chiarelli, E.; Cozzula, C.; Cunsolo, F.; Elek, N.I.; Mantovani, F.; Padoan, M.; Paletta, M.G.; Pezzi, M.; et al. Effects of Restoration Through Nature-Based Solution on Benthic Biodiversity: A Case Study in a Northern Adriatic Lagoon. *Water* **2025**, *17*, 366. [Google Scholar] [CrossRef]
83. Boscolo Brusà, R.; Feola, A.; Cacciatore, F.; Ponis, E.; Sfriso, A.; Franzoi, P.; Lizier, M.; Peretti, P.; Matticchio, B.; Baccetti, N.; et al. Conservation actions for restoring the coastal lagoon habitats: Strategy and multidisciplinary approach of LIFE Lagoon Refresh. *Front. Ecol. Evol.* **2022**, *10*, 979415. [Google Scholar] [CrossRef]
84. Feola, A.; Ponis, E.; Cornello, M.; Boscolo Brusà, R.; Cacciatore, F.; Oselladore, F.; Matticchio, B.; Canesso, D.; Sponga, S.; Peretti, P.; et al. An Integrated Approach for Evaluating the Restoration of the Salinity Gradient in Transitional Waters: Monitoring and Numerical Modeling in the Life Lagoon Refresh Case Study. *Environments* **2022**, *9*, 31. [Google Scholar] [CrossRef]
85. Haines-Young, R.; Potschin, M.B. *Common International Classification of Ecosystem Services (CICES) V5.1 and Guidance on the Application of the Revised Structure*; Fabis Consulting Ltd.: Nottingham, UK, 2018. Available online: [www.cices.eu](http://www.cices.eu) (accessed on 15 June 2026). [Google Scholar]
86. Vacchi, M.; De Falco, G.; Simeone, S.; Montefalcone, M.; Morri, C.; Ferrari, M.; Bianchi, C.N. Biogeomorphology of the Mediterranean *Posidonia oceanica* seagrass meadows. *Earth Surf. Process. Landf.* **2017**, *42*, 42–54. [Google Scholar] [CrossRef]
87. Pergent-Martini, C.; Pergent, G.; Monnier, B.; Boudouresque, C.-F.; Mori, C.; Valette-Sansevin, A. Contribution of *Posidonia oceanica* meadows in the context of climate change mitigation in the Mediterranean Sea. *Mar. Environ. Res.* **2021**, *165*, 105236. [Google Scholar] [CrossRef] [PubMed]
88. Fourqurean, J.W.; Duarte, C.M.; Kennedy, H.; Marbà, N.; Holmer, M.; Mateo, M.A.; Apostolaki, E.T.; Kendrick, G.A.; Krause-Jensen, D.; McGlathery, K.J.; et al. Seagrass ecosystems as a globally significant carbon stock. *Nat. Geosci.* **2012**, *5*, 505–509. [Google Scholar] [CrossRef]
89. Röhr, M.E.; Holmer, M.; Baum, J.K.; Björk, M.; Boyer, K.; Chin, D.; Chalifour, L.; Cimon, S.; Cusson, M.; Dahl, M.; et al. Blue carbon storage capacity of temperate eelgrass (*Zostera marina*) meadows. *Glob. Biogeochem. Cycles* **2018**, *32*, 1457–1475. [Google Scholar] [CrossRef]

90. Macreadie, P.I.; Anton, A.; Raven, J.A.; Beaumont, N.; Connolly, R.M.; Friess, D.A.; Kelleway, J.J.; Kennedy, H.; Kuwae, T.; Lavery, P.S.; et al. The future of Blue Carbon science. *Nat. Commun.* **2019**, *10*, 3998. [Google Scholar] [CrossRef] [PubMed]
91. Krause-Jensen, D.; Duarte, C.M. Substantial role of macroalgae in marine carbon sequestration. *Nat. Geosci.* **2016**, *9*, 737–742. [Google Scholar] [CrossRef]
92. Zheng, Y.; Lu, W.; Wang, H. Biodiversity-Centered Blue Carbon Management in Vegetated Coastal Wetlands: A Review of Conservation, Restoration, Monitoring, and Climate Adaptation Across Mangroves, Seagrass Beds, and Salt Marshes. *Diversity* **2026**, *18*, 388. [Google Scholar] [CrossRef]
93. Gattuso, J.P.; Frankignoulle, M.; Smith, S.V. Measurement of community metabolism and significance in the coral reef CO<sub>2</sub> source–sink debate. *Proc. Natl. Acad. Sci. USA* **1999**, *96*, 13017–13022. [Google Scholar] [CrossRef]
94. Ware, J.R.; Smith, S.V.; Reaka, M. Coral reefs: Sources or sinks of atmospheric CO<sub>2</sub>? *Coral Reefs* **1992**, *11*, 127–130. [Google Scholar] [CrossRef]
95. zu Ermgassen, P.S.E.; McCormick, H.; Debney, A.; Fariñas-Franco, J.M.; Gamble, C.; Gillies, C.; Hancock, B.; Laugen, A.T.; Pouvreau, S.; Preston, J.; et al. European Native Oyster Reef Ecosystems Are Universally Collapsed. *Conserv. Lett.* **2025**, *18*, e13068. [Google Scholar] [CrossRef]
96. Gravina, M.F.; Cardone, F.; Bonifazi, A.; Bertrandino, M.S.; Chimienti, G.; Longo, C.; Nonnis Marzano, C.; Moretti, M.; Lisco, S.; Moretti, V.; et al. *Sabellaria spinulosa* (Polychaeta, Annelida) reefs in the Mediterranean Sea: Habitat mapping, dynamics and associated fauna for conservation management. *Estuar. Coast. Shelf Sci.* **2018**, *200*, 248–257. [Google Scholar] [CrossRef]
97. Franzitta, G.; Colletti, A.; Savinelli, B.; Lo Martire, M.; Corinaldesi, C.; Musco, L. Feasibility of the Sabellarid Reef Habitat Restoration. *Front. Mar. Sci.* **2022**, *9*, 854986. [Google Scholar] [CrossRef]
98. Pogoda, B.; Brown, J.; Hancock, B.; Preston, J.; Pouvreau, S.; Kamermans, P.; Sanderson, W.; von Nordheim, H. The Native Oyster Restoration Alliance (NORA) and the Berlin Oyster Recommendation: Bringing back a key ecosystem engineer by developing and supporting best practice in Europe. *Aquat. Living Resour.* **2019**, *32*, 13. [Google Scholar] [CrossRef]
99. Archetti, R.; Buccino, M.; Casadei, I.; Gaeta, M.G.; Tuoizzo, S.; Ponti, M. Optimal Layout of Limestone Substrates for Oyster Beds as Nature-Based Solutions for Coastal Management. *Coast. Eng. Proc.* **2025**, *38*, 50. [Google Scholar] [CrossRef]
100. van der Meulen, F.; Salman, A. Management of Mediterranean coastal dunes. *Ocean Coast. Manag.* **1996**, *30*, 177–195. [Google Scholar] [CrossRef]
101. Tereszkiwicz, P.; Provost, L.; Everett, C. *Coastal Sand Dunes: A Review of Management Strategies for Dune Stabilization*; Technical Note ERDC/TN EWN-25-5; U.S. Army Engineer Research and Development Center: Vicksburg, MS, USA, 2025. [Google Scholar]
102. PAP/RAC. *Nature-Based Solutions for Climate Change Adaptation in Mediterranean Coastal Typologies*; Integrated Coastal Zone Management Protocol Technical Report; PAP/RAC: Split, Croatia, 2024. [Google Scholar]
103. United Nations Environment Programme. *The Economics of Nature-Based Solutions: Current Status and Future Priorities*; United Nations Environment Programme: Nairobi, Kenya, 2020. [Google Scholar]
104. Green Climate Fund. *Funding Proposal FP068: Enhancing Climate Change Adaptation in the North Coast and Nile Delta in Egypt*; GCF/United Nations Development Programme (UNDP): Incheon, Republic of Korea, 2018. Available online: <https://www.greenclimate.fund/project/fp068> (accessed on 27 June 2026). [Google Scholar]
105. World Bank Group. *Egypt, Arab Republic of-Country Climate and Development Report: Background Note-A People-Centered Green Transformation*; World Bank Group: Washington, DC, USA, 2023. Available online: <http://documents.worldbank.org/curated/en/099222103142327400> (accessed on 30 June 2026). [Google Scholar]
106. United Nations Development Programme (UNDP). *Enhancing Climate Change Adaptation in the North Coast and Nile Delta in Egypt. Final Project Implementation Report*; UNDP: Cairo, Egypt, 2024. Available online: <https://www.undp.org/egypt/projects/enhancing-climate-change-adaptation-north-coast-and-nile-delta-egypt> (accessed on 30 June 2026). [Google Scholar]
107. Giupponi, C.; Bidoia, M.; Breil, M.; Lamperti, F.; Marani, M.; Massarutto, A.; Mysiak, J.; Passadore, G.; Roson, R.; Stellin, G. Boon and burden: Economic performance and future perspectives of the Venice flood protection system. *Reg. Environ. Change* **2024**, *24*, 44. [Google Scholar] [CrossRef]
108. Baldassarre, L.; Natali, V.; De Pascale, F.; Vezzi, A.; Banchi, E.; Bazzaro, M.; Relitti, F.; Tagliapietra, D.; Cibic, T. The Impact of MOSE (Experimental Electromechanical Module) Flood Barriers on Microphytobenthic Community of the Venice Lagoon. *Microorganisms* **2023**, *11*, 936. [Google Scholar] [CrossRef] [PubMed]
109. Tognin, D.; Finotello, A.; D’Alpaos, A.; Viero, D.P.; Pivato, M.; Mel, R.A.; Defina, A.; Bertuzzo, E.; Marani, M.; Carniello, L. Loss of geomorphic diversity in shallow tidal embayments promoted by storm-surge barriers. *Sci. Adv.* **2022**, *8*, eabm8446. [Google

Scholar] [CrossRef] [PubMed]

110. Chao, Z.; Shi, D.; Fowmes, G.J. Mechanical behaviour of soil under drying–wetting cycles and vertical confining pressures. *Environ. Geotech.* **2024**, *11*, 714–724. [Google Scholar] [CrossRef]
111. Chao, Z.; Wang, H.; Hu, S.; Wang, M.; Xu, S.; Zhang, W. Permeability and porosity of light-weight concrete with plastic waste aggregate: Experimental study and machine learning modelling. *Constr. Build. Mater.* **2024**, *411*, 134465. [Google Scholar] [CrossRef]
112. Shi, D.; Wang, H.; Fowmes, G.J.; Chao, Z. The pull-out mechanical properties of the interface between geogrid and calcareous sand considering temperature effects. *Acta Geotech.* **2025**, *21*, 713–743. [Google Scholar] [CrossRef]

**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.