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The Green Infrastructure of Sandy Coastlines: A Nature-Based Solution for Mitigation of Climate Change Risks

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Abstract: Natural coastal landforms such as sand dunes and sandy beaches have been proposed as green infrastructure that can reduce climate change risks along coastlines. As such, they can offer a nature-based solution to rising sea levels, increased storminess and wave erosion associated with climate change. However, these proposed advantages are not always based on a sound understanding of coastal sediment system dynamics or tested against field evidence of coastal morphodynamic behavior. This study critically examines the basis of the claim for coastal landforms as green infrastructure, by considering how and in what ways these landforms provide resilience against ongoing climate change along sandy coasts, and proposes a theoretical framework for understanding this relationship. The analysis highlights that natural coastal landforms do not always have properties that provide resilience against future climate change. They can only be considered as offering nature-based solutions against climate change when their pre-existing morphodynamic behavior is fully understood. Thus, not all coastal landforms can be considered as 'green infrastructure' and the resilience offered by them against climate change forcing may vary from one place or context to another. This should be considered when using landforms such as sandy beaches and sand dunes as nature-based solutions for coastal management purposes. A 10-step framework is proposed, guiding coastal managers on how such green infrastructure can be used to mitigate climate change risks along coasts.

Keywords: beaches; climate change; coastal change; green infrastructure; morphodynamic behavior; nature-based solutions; sand dunes; sandy coastlines; sediment systems

Citation: Knight, J. The Green Infrastructure of Sandy Coastlines: A Nature-Based Solution for Mitigation of Climate Change Risks. *Sustainability* **2024**, *16*, 1056. https://doi.org/10.3390/su16031056

Academic Editors: Kim Neil Irvine, Niall Kirkwood and Lloyd Hock Chye Chua

Received: 22 December 2023
Revised: 12 January 2024
Accepted: 24 January 2024
Published: 25 January 2024

1. Introduction

Coastlines lie at the interface of land and sea and this means that coastal geomorphic systems can potentially be affected by both terrestrial and marine forcings [1,2] (Figure 1). For example, rainfall inland can change river and sediment discharge to the coast and, therefore, estuary and beach sediment supply and the morphodynamic behavior of these landforms [3–5]. Low pressure weather systems developed offshore can lead to strong winds, large waves and storm surges approaching the coastline and these can, in turn, lead to coastal erosion and flooding as well as rapid and significant impacts on people and infrastructure [6,7]. Apart from climatic forcings, coasts are also increasingly affected by direct human activity. This includes land use change, urbanization and infrastructure development [8]. These non-climatic forcings can also lead to changes in coastal geomorphology and sediment systems, which can have an impact on the ability of coastlines to withstand climate and weather events, termed their *resilience* [9–11]. This specific concept is explained in more detail below. Figure 1 highlights that the interplay between climatic and non-climatic forcings from land and sea have potential to impact on coastlines globally and sometimes in very rapid and complex ways. For example, an exposed rock cliff is highly susceptible to wave undercutting and rapid collapse [12]. However, the presence of talus at the cliff foot can reduce subsequent wave exposure and erosion risk, thereby forming a cycle of cliff behavior that is driven by intrinsic changes in cliff-face resilience rather than by any change in external boundary conditions (i.e., waves continue to approach the cliffed coast regardless). Likewise, catchment deforestation can give rise to dramatically increased rates of soil erosion and fluvial sediment yield to the coastline [13,14], building deltas, beaches and sand dunes. On the one hand, their greater height and volume may make them more resilient to withstand wave attack and sea-level rise; on the other hand, a greater sand volume may lead to increased longshore sediment yield and thus increased erosion rates [15,16]. Disentangling these different factors and their relationships is a fundamental requirement in understanding coastal systems.

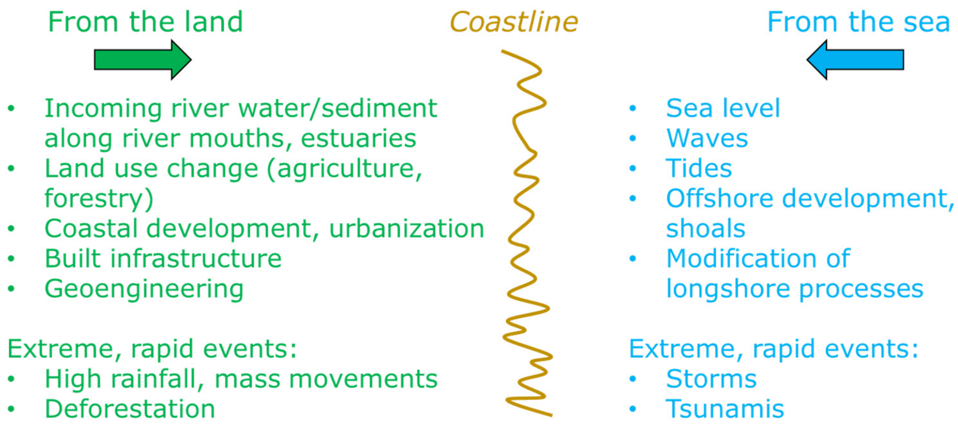

Figure 1. Illustration of the nature of different forcing factors that influence sandy coasts. The interplay between these factors is discussed in the text.

The forcing–response relationships between coastlines and climate have been examined in many different contexts, including with respect to patterns and rates of coast erosion; changes in beach, dune and barrier morphology; sediment flux calculation; flood inundation risk; and coastal ecosystems [16–20]. The co-variability between coastal change and the different climatic forcing factors that impact the coastline (sea level, storms, waves) has been used to construct empirical models that, in theory, can then be used to predict coastline responses under changes in coastal forcing [21–24]. For example, anthropogenic climate change is currently leading to increases in sea levels globally as well as locally [25,26] and increased sea surface temperatures are increasing the frequency and magnitude of storms generated over the open ocean (including subtropical cyclones and hurricanes) [27,28]; this in turn is increasing significant wave height (thus energy) and erosion rates [29,30]. The outcome is an amplification of land and ocean forcings that is increasingly leading to greater and more unpredictable variability in the workings of coastal systems, impacting on their physical properties and human activity alike [31,32].

This theoretical understanding between climate and coastal change, however, involves a number of key assumptions. Empirical models commonly assume linear and deterministic responses to climate forcing. However, this represents a relatively simple and narrow viewpoint of coastal response to climate forcing that does not fully consider the varied ways in which ongoing climate change may impact on coastal processes and properties [33–36]. Models are also founded on the assumption of an immediate geomorphic response to forcing; however, in reality, time lags exist in the workings of all physical systems [35,37] and these are significant because they mean that many landforms may be considered as relict and not at equilibrium with respect to prevailing climatic or environmental conditions. This has implications for how the sensitivity of different landforms to climate forcing might be evaluated.

Along coastlines, understanding of climate forcing–response relationships are of particular relevance for several reasons. They can: (1) help in conceptualizing and predicting the future evolution of coastal systems under different climate change scenarios; (2) enable the better monitoring and modeling of the rates and locations of geomorphic change as a result of sediment erosion and deposition processes; (3) help evaluate the effects of climate change on coastal landforms and ecosystems, including ecosystem services, biodiversity and carbon storage; (4) understand and reduce coastal hazard risk; (5) enable better decision making by coastal managers when fuller information on coastal systems is available; and (6) facilitate the sustainable use of coastal resources by local communities.

For these reasons, understanding how coastal landforms respond to climate, especially as a result of global warming, is needed in order to identify and enact appropriate coastal management strategies. A key limitation, however, is the absence of a firm theoretical understanding of coastal systems and how they respond to climate [22]. This represents the research problem investigated in this study. In detail, the study aims are to (1) describe the dynamics of coastal systems and the sensitivities exhibited by different coastline types and their relationship to resilience, (2) identify how to build coastal resilience along different coastlines, with specific reference to sandy coasts, and (3) discuss how coastal landforms as 'green infrastructure' can provide a nature-based solution for climate change-induced risks.

2. Methodological Approach

This study is based on conceptual analysis of coastal systems, landforms and morphodynamics supported by case studies from the existing literature and original field observations, in particular, from sandy coasts along different coastlines globally. The analysis developed in this study is supported by development of a new conceptual model for understanding the relationship between resilience of coastal morphodynamics and a new practical 10-step guide for enacting nature-based management solutions for the impacts of climate change on sandy coastlines. This will be of relevance to both coastal scientists and managers.

3. Coastal Systems

Coastal sediment cells operate on the basis of wind-, wave- and tide-mobilized sediments that follow the direction of energy transmission and fluid transport within the system [20,35,38] (Figure 2). This means that coastal sediment dynamics are founded on the interplay between sediment properties such as grain size, and hydrodynamic forcing factors that are, in this case, mainly climate driven [39]. Although coastal sediment cells can be considered as integrated and interconnected systems [35], in reality, the sediment volume fluxes and flux rates are highly variable between different storage areas within the system and respond to different forcing factors, such as wave-climate-controlling shoreface erosion and longshore transport [39,40] and wind-regime-controlling beach–dune sediment dynamics [41]. Understanding coastal sediment dynamics is the basis for modeling and predicting coastal change [22,42–45].

The most typical way in which changes in coastal properties can be identified and quantified is through changes in coastal sediment systems and, therefore, landform patterns. Any landform has a morphological expression and thus its shape and relief can be mapped in the landscape. In some instances, the three-dimensional shape can also be identified, which allows for sediment volume to be calculated. Morphological mapping of coastal landforms has been done based on field and remote sensing methods [46–48] and this can enable rates of morphological change to be calculated. This has been done, for example, for mobile and unvegetated transverse sand dunes located in the upper supratidal zone of sandy beaches, where longshore winds drive migration of the dune form, seen through changes over time in the position of the dune crestline and its rotation with respect to the shoreline [20].

Different coastal types exhibit different styles of morphodynamic behavior and thus have different responses to climate forcing. For example, *rocky coastlines* have a higher rock mass strength and so have highly variable event-scale erosion rates that are low when averaged over long time periods, and are more strongly affected by long-term weathering [49]. Rock coasts are relatively stable under 'average' climatic and hydrodynamic conditions and thus exhibit lower sensitivity to climate forcing. Their landforms may be relict, where they exist relatively unchanged for long periods of time, and thus have higher preservation potential (Figure 3a,b). *Sandy coastlines* are more easily eroded because of the presence of unconsolidated, loose sand grains and exhibit a quicker morphodynamic response to climate forcing, reflecting higher sensitivity, for example, when surface sand grains are moved around rapidly by individual waves (Figure 3c,d). This means the landforms of sandy coastlines may exhibit quasi-equilibrium where they respond rapidly to a range of changeable forcings. The processes and rates of *mixed coastlines* are more variable, largely because they are influenced by the distribution and size of bedrock outcrops, with loose sand occupying the hollows between the outcrops, or more commonly by the presence of gravel patches or strips as well as sand (Figure 3e,f). Sand and gravel/bedrock exhibit very different morphodynamic responses to the coastal wave regime.

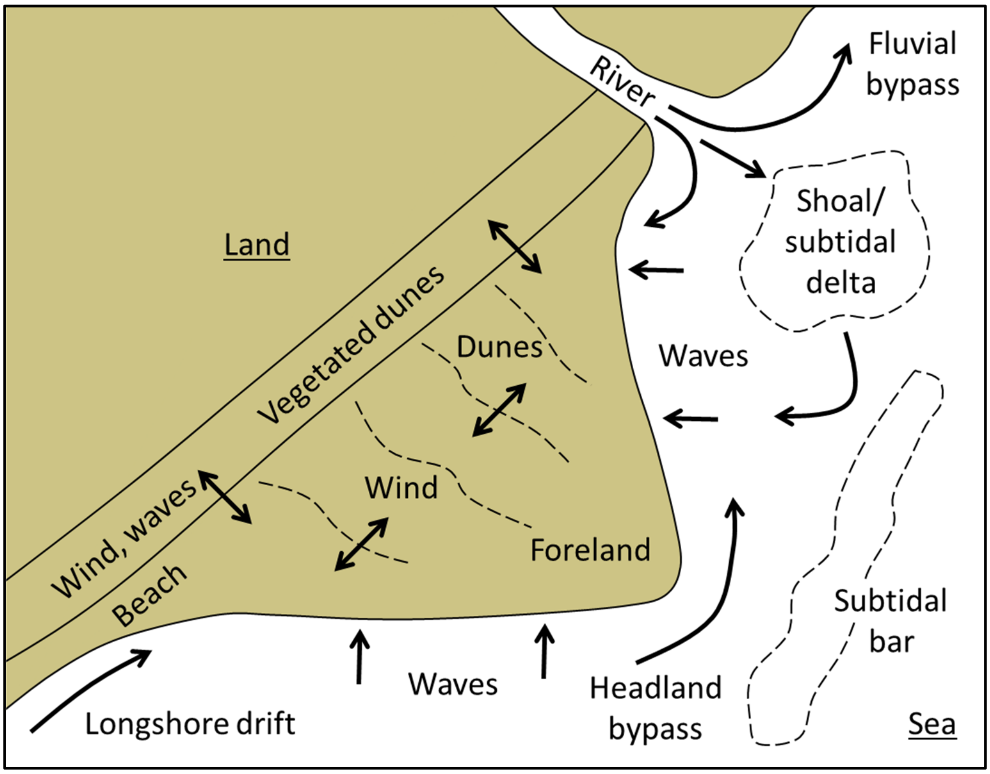

Figure 2. Schematic illustration of typical sandy coast sediment dynamics (redrawn from [20]).

In addition to variations in sensitivity to forcing imparted by rocky *versus* sandy and mixed coasts, different coastline-facing directions and nearshore bathymetries can also lead to variations in shoreface energy and the potential for sediment erosion and transport [45,50]. In closed sediment cells, erosion in one place should, in theory, be balanced by deposition elsewhere [35,43]. This should, in theory, mean that different sandy landforms may experience different trajectories of change (erosion, deposition), even under the same forcing regime. In many instances, however, the lateral and seaward margins of sediment cells are not clearly defined and may vary in extent if coastal energy availability changes [46]. This means that volume flux approaches to nearshore sand dynamics cannot be used uncritically as a proxy for the sensitivity of a coastal system to climate forcing.

However, despite this understanding of the workings of coastal systems and sediment cells, some problems still exist. (1) As different coastal landforms have different properties and levels of sensitivity to climate forcing, they will respond differently to weather and climate events, even along the same coastal stretch. This means there may be a low predictability of the net coastal response to climate forcing. This is amplified by any feedbacks that may exist between the different elements within that sediment cell (Figure 2). (2) Coastal systems are all, to some extent, relict or exhibit delayed responses to forcing, meaning that the measurement and monitoring of such systems may not reveal their true sensitivity to forcing. (3) Coastlines also have varying types and degrees of human activities, and this is known to be a factor in changing coastal system behavior and in often unpredictable and nonlinear ways [51]. (4) Climate is a non-stationary forcing factor and ongoing climate change is increasing coastal energy and, therefore, increasing the rate of coastal change. However, this response is not uniform and likely shows an increasing level of variability over time.

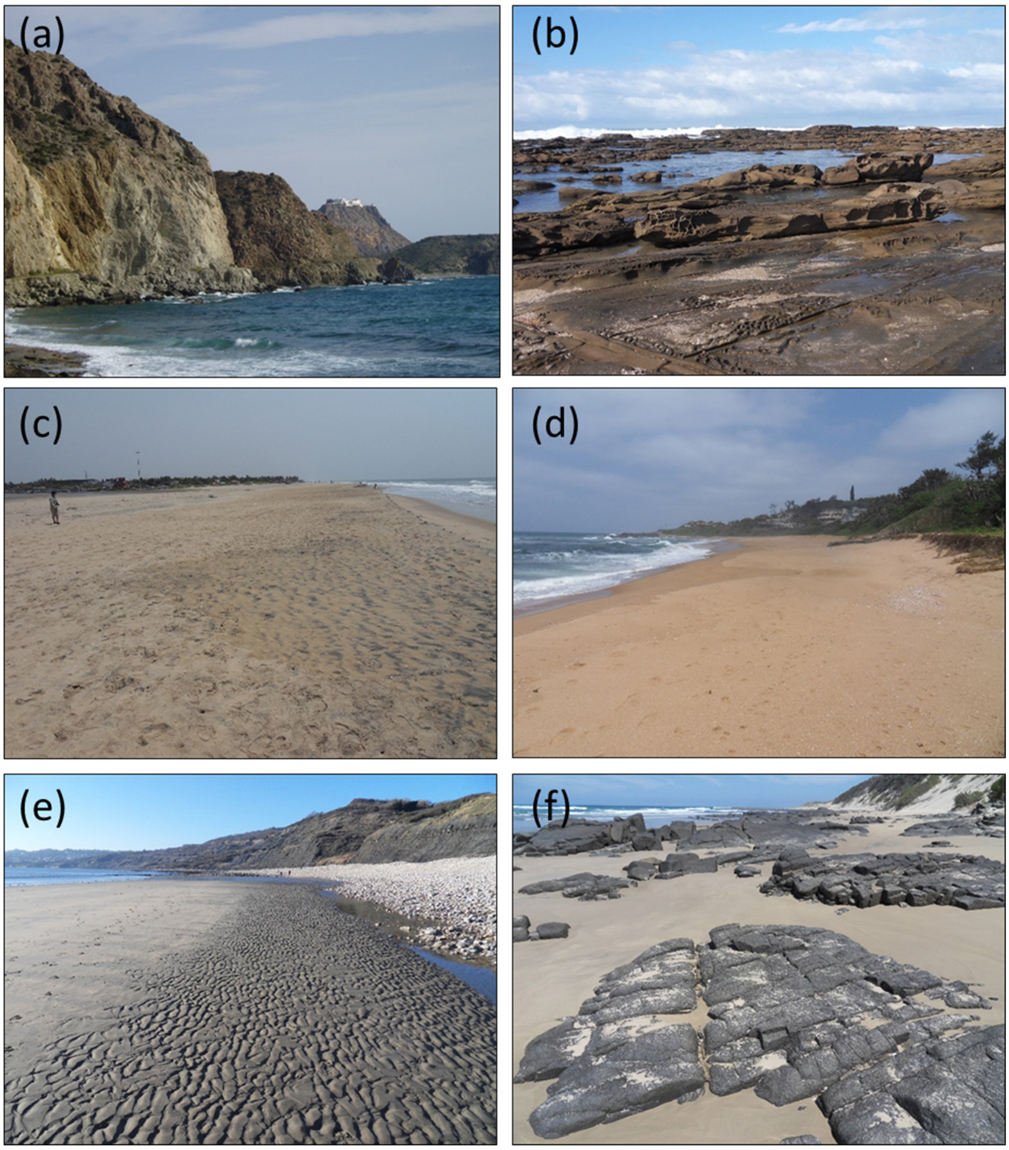

Figure 3. Examples of the three major coastal types. (**a**) Steep rock cliff (southeast Spain), (**b**) rocky shore platform, where the cliffline has retreated back, forming the platform surface (southern South Africa), (**c**) wide and shallow beach with backing vegetated sand dunes (southeast India), (**d**) narrow and steep beach with an eroded and vegetated cliffline at the back of the beach (northeast South Africa), (**e**) mixed beach environment, where both seaward sand and a landward gravel beach element are present (southern UK), and (**f**) mixed beach, where patches of sand are located between subdued bedrock outcrops (southern South Africa).

4. Coastline Resilience

To help explain climate forcing–coastal response relationships, the concept of coastal resilience can be considered. Coastal resilience refers to the ability of all types of coastal systems (geomorphic, sedimentary, ecological, socioeconomic) to withstand disturbance by different forcing factors [10,52,53]. As such, coastal resilience is related to the physical attributes of coastlines such as landforms and ecosystems; coastal assets and infrastructure, such as roads and railways; and coastal communities and people [53]. Coastal resilience can be evaluated indirectly through examining any changes that take place to the system or its workings as an outcome of forcing. For example, if a weather or climate event occurs, how does the coastal system respond? If the system changes quickly and dramatically, then it is considered that the system has low resilience (high sensitivity) [54]. If the system's response is subdued and/or delayed, then it shows high resilience (low sensitivity) [11]. This provides a conceptual framework for considering forcing–response relationships.

If coastlines have higher resilience, they will be more likely to withstand coastal forcing and less likely to exhibit change or lead in negative outcomes as a result of that change. However, ongoing global warming means that there is a sustained increase in climate forcing along coasts (and in other physical environments globally), and this increases the likelihood that critical geomorphic thresholds within the system will be exceeded and coastal change will occur [53]. The outcome of ongoing global warming is that coastal resilience is weakened and rapid coastal change is both becoming more commonplace and occurring more rapidly. This has been identified in many studies globally [16,31].

Several studies have also considered how resilience can be enhanced along different types of coasts [11]. *Sandy beaches* can be nourished by dredging/pumping, building groynes, planting of the supratidal zone, building or maintaining offshore shoals/surf breaks and stabilizing the landward position of the beach with a sloping seawall, gabion, riprap, engineered beach ridge, low dune or sand fence [15] (Figure 4). The outcome of these actions is that beach volume increases, serving as a wider or higher barrier against the land. *Sand dunes* can experience revegetation/planting of degraded areas, planting and wind fencing to encourage embryo dune growth, engineering of artificial dunes, restrictions on groundwater extraction, maintaining dune slacks and ponds and constructing and maintaining boardwalks/fences to restrict disturbance [55–57]. All of these actions serve to stabilize the land surface and decrease the likelihood that the dune body is affected by water or wind erosion. *Rocky shorelines* can be made more resilient through armoring on the landward edge of rock platforms, monitoring unstable cliffs or caves, using rock bolts or other geotechnical strategies to increase slope stability, enhancing biodiversity through building artificial pools and reducing risk to people by providing safety equipment and warning signage. All of these strategies in different coastal environments focus on enhancing the natural and pre-existing properties of the coast in order to increase its resilience.

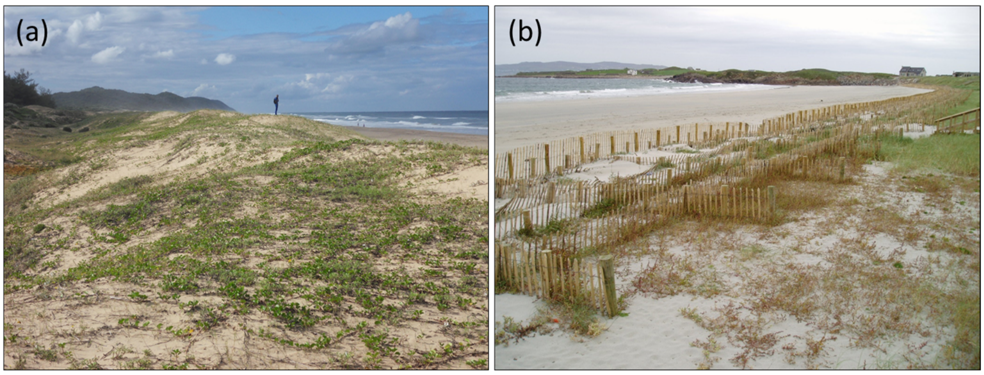

Figure 4. Examples of sandy coastal landforms that represent 'green infrastructure' that increases coastal resilience to climate forcing. (**a**) A natural beach berm in northeast South Africa, partly vegetated by *Scaevola plumieri* (gullfeed), (**b**) embryo dunes in northwest Ireland with sand fences and planted with *Ammophila arenaria* (European marram grass).

Relationships between coastal sensitivity and resilience can be explored through considering how a sand dune environment develops over time, in both its physical and ecological properties (Figure 5). This model shows that the sensitivity of a dune system generally decreases over time as the dune body builds up and becomes vegetated through primary and secondary succession [55]. However, a sudden disturbance by erosion or land use change results in a dramatic increase in system sensitivity (a lowering of system resilience) that makes it highly vulnerable to a loss of physical and ecological integrity and ecosystem services [58].

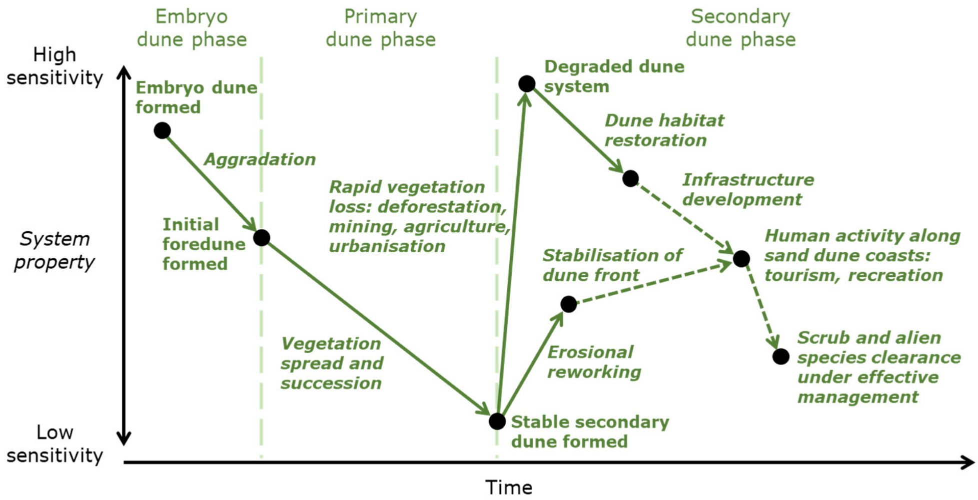

Figure 5. Conceptual model describing changes in coastal sand dune sensitivity to forcing over time as a result of both climatic and non-climatic forcing factors (e.g., Figure 1). Evolution of the sand dune environment from embryo to primary and secondary dune phases (words in bold, not italics) is plotted in non-dimensional phase space; no specific scale is implied. Green arrows show trajectories of evolution. Words in bold italics describe the processes taking place along these trajectories. Dotted green arrows indicate the role of decision making in dune management that can influence future dune system sensitivity.

5. Discussion

5.1. Building Coastal Resilience with Nature

Increasing the resilience of coastlines, including its landforms, is a key strategy to decrease the (negative) impacts of climate change, including higher rates of coastal erosion caused by rising sea levels and increased storminess [11,59,60]. Seeking ways in which coastal resilience can be increased by maintaining coastal landforms as green infrastructure may potentially have the impact of reducing the natural variability of the system and reducing the likelihood of extreme events affecting it [60,61] (Figure 6). Figure 6 shows that enhanced climate forcing as a result of global climate change in the 21st Century results in increased variability of coastal system responses, in particular, a higher frequency of extreme events such as coastal erosion/deposition or cliff collapse, the spread of invasive species or the local extinction of endemic species. Increasing the natural resilience of the coastline through the use of green infrastructure can make the coastline better able to withstand climate forcing and thus reduces the variability of coastal responses to this forcing (i.e., reduces coastal sensitivity, see Figure 5).

All coastal landforms exhibit natural morphodynamic variability, but appropriate soft engineering strategies can enhance coastal landform and ecosystem properties and thereby result in greater resilience [11,15,62]. These strategies focus on building and stabilizing landform surfaces by increasing their volume or height or by revegetation [63–65]. In so doing, these landforms and ecosystems can be considered as 'green infrastructure', serving the same function as hard engineering structures traditionally used for coastal management and protection [64,66–68]. The detailed strategies employed in the use of green infrastructure are dependent on the coastal element examined (i.e., beach, dune, saltmarsh), the specific end goal to be achieved and any constraints such as budget, timeframe, community priorities or the presence of rare species.

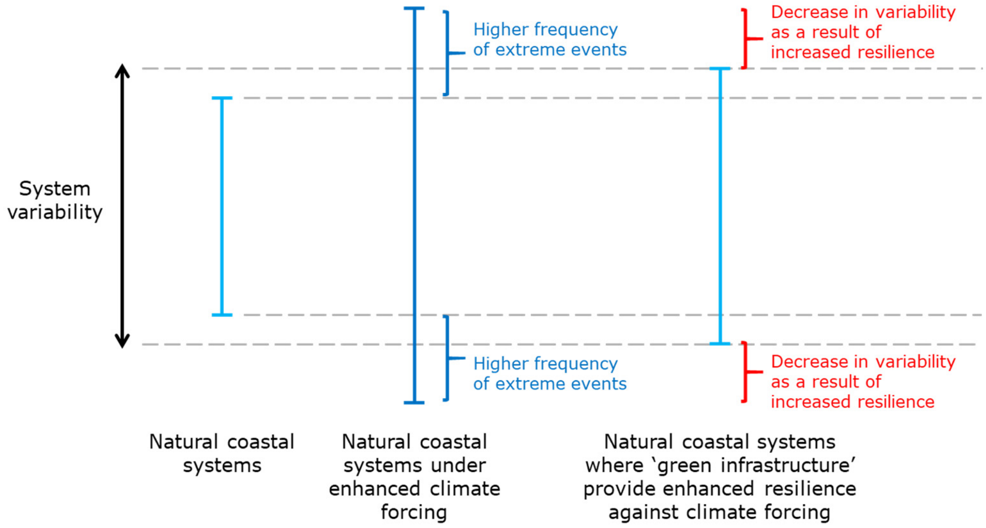

Figure 6. Conceptual model of coastal system responses to climate forcing and the role of green infrastructure in increasing coastal resilience.

5.2. Green Infrastructure as a Nature-Based Solution for Climate Change Impacts along Sandy Coastlines

Exploiting the natural resilience afforded by the 'green infrastructure' of coastlines can be considered as an example of a 'nature-based solution' (NBS) to coastal issues [69–71]. Many studies worldwide have discussed the advantages of NBS along coastlines and the emphasis has mainly been on sandy coasts, including beaches, sand dunes, saltmarsh and mangroves [15,56,69,72–74], where there is a close relationship between climate forcing and sediment dynamic response [75,76]. In contrast, there is much less consideration of the application of NBS to rock coasts and none at all to the rapidly changing environments of deltas or arctic coasts. The major advantages of NBS along coastlines are that (1) it is cheaper, more cost-effective and less risky a management strategy and with lower uncertainty; (2) it is easier to implement and requires less technology; (3) it results in more positive and fewer negative outcomes, including for ecosystems; and (4) it can involve local stakeholders and communities more easily in decision making, management and monitoring [77–80]. Most previous deployment of NBS along coasts has taken place in the USA and with an emphasis on the monitoring strategies used to evaluate coastline dynamics before, during and after any NBS intervention [81]. For example, island restoration in Chesapeake Bay (MD, USA) used dredged sediment to build up island beaches, which increased the size and height of sandy landforms, increased vegetation biomass and decreased the efficacy of wave erosion [82]. NBS strategies have been particularly applied to coastal wetlands and intertidal environments which are sensitive to subtle changes in sediment supply and micro-elevation, with implications of high-biodiversity intertidal ecosystems [72,73,76]. These examples highlight the multiple benefits and the cost-effectiveness of NBS in certain types of coastal settings.

A proposed sequence of methodological steps for enacting NBS against climate change impacts along coasts is shown in Table 1. This 10-step plan shows that to use NBS as an effective management approach, one needs to first understand the coastal properties, processes and morphodynamics in the context of systems. These sequential steps also highlight the importance of a monitoring plan for coastal observation, as well as the active engagement of local communities. The reasons why these steps are necessary are that different coastal stretches work in different ways and the solutions used for one coastline may not be applicable elsewhere, and that different coastal stretches will have different issues and priorities, related, in particular, to human activity. It is, therefore, important to work with and empower local communities and stakeholders in establishing priorities and building sustained and collaborative partnerships. It also highlights that decision making without scientifically valid and up-to-date information is flawed and will invariably fail [82–84].

Table 1. The sequence of steps used in enacting nature-based solutions through effective management against climate change impacts along coastlines.

Step #	Description of the Activity
1	Investigation, mapping and inventorizing of coastal landforms and properties at a specific site or coastal stretch, based on field observations and measurements. This constitutes environmental auditing of coasts as a first activity.
2	Liaising with local communities, with the aim of understanding the community use of coastal resources and the values ascribed to coastal landforms, ecosystems and aesthetics in that area.
3	Identifying coastal management goals with respect to international, national and local guidelines and strategies and agreeing these with relevant stakeholders at all levels.
4	Monitoring of coastal change and coastal process dynamics over different spatial and temporal scales using field and/or remote sensing methods. This can also include citizen science methods undertaken with the involvement of local communities.
5	Calculation of rates and locations of change, based on data obtained in step 4, and development of numerical models to simulate these changes and to predict future change, including changes in external boundary conditions (e.g., climate) and changes in coastal properties.
6	Identification of the most and least resilient coastal landforms and properties based on their morphodynamic behavior, based on data obtained in steps 4 and 5.
7	Identification of a coastal management plan that considers the most resilient landforms and properties as green infrastructure and that works with the natural resilience of these landforms. This management plan satisfies the requirements of the goals identified in step 3.
8	Enacting the management plan and monitoring its effectiveness based on achievement of management goals (including measurable performance indicators and timeframes) identified in step 7.
9	Communication of decision-making processes and interim and long-term outcomes with local communities, including dealing with and identifying solutions for any problems or delays that may arise.
10	Learning from mistakes and/or successes in order to identify lessons that can be applied elsewhere in similar contexts. This can include development of management handbooks or similar tools that can be communicated to stakeholders, e.g., [85].

5.3. Limitations of the Nature-Based Solutions Approach

Nature-based solutions (NBS) represent the best approach to enhance coastal resilience by supporting the natural geomorphological and ecological processes along coastlines and enhancing coastal properties. However, it is founded on an understanding of physical systems and scientific information on that coastal stretch, which may be limited or absent, particularly in the developing world. An absence of information will limit the ability of numerical models or coastal managers to predict the future state of the coastline under ongoing climate forcing or to identify any future vulnerabilities/resilience or geomorphic thresholds that may lead to a tipping point in coastal system behavior, such as triggering a switch between aggradation and erosion [36]. It also emphasizes that a 'one size fits all' approach for coastal management does not work, for example, where a national-scale and top-down strategy is applied to all areas regardless of their properties or needs, which remains the prevailing approach to coastal management globally [60].

At each step of the management process (Table 1), there may be uncertainty in the information or data used. This includes uncertainty in the trajectory of future changes related to climate forcing (e.g., sea-level rise, storminess), land use change and urbanization. It is also important to note that changes in political priorities may lead to certain management approaches being adopted (such as building a sea wall), whether or not it is appropriate [60,86,87]. This is because, from the viewpoint of politicians and local communities, NBS and enhancing the natural resilience of pre-existing coastal properties may be considered as a 'do nothing' approach rather than something that yields an immediate and decisive response to an issue of coastal erosion [87]. Communication and education is, therefore, needed, which is why engaging with communities and stakeholders is important [69] (Table 1). In addition, not all landforms or coastal settings are suitable for NBS to be deployed and the resilience offered by different 'green infrastructure' may vary from one place or context to another. NBS should therefore be considered as part of a wider portfolio of coastal management strategies [67].

6. Conclusions and Future Research Directions

Nature-based solutions for managing the impacts of climate change and climate and weather events along coasts are founded on the use of pre-existing coastal properties and landforms as 'green infrastructure' that can lead to greater coastline resilience and, therefore, decreased climate impacts. The significant advantages of a NBS approach are that it works with rather than against nature and can enhance coastal geodiversity, biodiversity, ecosystem services and sediment system functionality [81].

The major disadvantages are that it requires detailed knowledge and understanding of specific coastal situations, as well as continuous monitoring, and may be seen politically as a 'do nothing' approach. More research is needed on the applicability of NBS in different coastal settings and on developing a more rigorous framework for engaging with local communities and stakeholders through the management process (Table 1).

The integrated and multidisciplinary approach afforded by NBS means that site-based data on a range of coastal properties and processes are needed. This may include microclimate, geology, geomorphology, sediment dynamics, ecosystems, ecosystem services, hydrodynamics, water chemistry, patterns of human activity and how people engage with the coastal space, tourism and coastline aesthetics. Building relationships with coastal user communities and stakeholders is the most promising way for the NBS approach to gain traction at the local level. However, this element is often sidelined in all types of coastal management approaches and requires continuous and consistent strategic engagement [85,88].

The wider context of NBS along coastlines globally is its contribution to sustainability goals, including maintaining environment quality for ecosystems and people alike. Coastlines historically are sites of human occupation, culture and heritage and, thus, the maintenance of coastal systems goes beyond the mere functional to other aspects of landscape and environmental properties, including how people use and value the natural world, its properties and processes [89]. This aspect has been less fully considered in designing NBS, but it is key to maintaining sustainable socioeconomic activity along coasts, such as tourism, that seek value in the environment rather than degrading the environment (Figure 5).

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Kron, W. Coasts: The high-risk areas of the world. *Nat. Haz.* **2013**, *66*, 1363–1382. [CrossRef]
2. Ramesh, R.; Chen, Z.; Cummins, V.; Day, J.; D'Elia, C.; Dennison, B.; Forbes, D.L.; Glaeser, B.; Glaser, M.; Glavovic, B.; et al. Land–Ocean Interactions in the Coastal Zone: Past, present & future. *Anthropocene* **2015**, *12*, 85–98.

3. Cooper, J.A.G.; Mason, T.R.; Reddering, J.S.V.; Illenberger, W.K. Geomorphological effects of catastrophic flooding on a small subtropical estuary. *Earth Surf. Proc. Landf.* **1990**, *15*, 25–41. [CrossRef]
4. Kennedy, D.M.; McSweeney, S.L.; Mariani, M.; Zavadil, E. The geomorphology and evolution of intermittently open and closed estuaries in large embayments in Victoria, Australia. *Geomorphology* **2020**, *350*, 106892. [CrossRef]
5. Ngobeni, D.; Knight, J. Evaluation of river mouth dynamics along the Eastern Cape coastline, South Africa. *Trans. R. Soc. S. Afr.* **2023**, *78*, 167–180. [CrossRef]
6. Corbella, S.; Stretch, D.D. Shoreline recovery from storms on the east coast of Southern Africa. *Nat. Haz. Earth Syst. Sci.* **2012**, *12*, 11–22. [CrossRef]
7. Lindner, B.L. Climatology and variability of tropical cyclones affecting Charleston, South Carolina, from 1670 to 1850. *J. Coast. Res.* **2019**, *35*, 397–409. [CrossRef]
8. Close, S.L.; Montalto, F.; Orton, P.; Antoine, A.; Peters, D.; Jones, H.; Parris, A.; Blumberg, A. Achieving sustainability goals for urban coasts in the US Northeast: Research needs and challenges. *Local Environ.* **2017**, *22*, 508–522. [CrossRef]
9. Flood, S.; Schechtman, J. The rise of resilience: Evolution of a new concept in coastal planning in Ireland and the US. *Ocean Coast. Manag.* **2014**, *102*, 19–31. [CrossRef]
10. Schultz, M.T.; Smith, E.R. Assessing the resilience of coastal systems: A probabilistic approach. *J. Coast. Res.* **2016**, *32*, 1032–1050. [CrossRef]
11. Knight, J. Nature-based solutions for coastal resilience in South Africa. *S. Afr. Geogr. J.* 2024, *in press*. [CrossRef]
12. Emery, K.O.; Kuhn, G.G. Sea cliffs: Their processes, profiles, and classification. *Geol. Soc. Am. Bull.* **1982**, *93*, 644–654. [CrossRef]
13. Knight, J.; Harrison, S. Sediments and future climate. *Nat. Geosci.* **2009**, *3*, 230. [CrossRef]
14. Addad, J.; Martins-Neto, M.A. Deforestation and coastal erosion: A case from east Brazil. *J. Coast. Res.* **2000**, *16*, 423–431.
15. Hanley, M.E.; Hoggart, S.P.G.; Simmonds, D.J.; Bichot, A.; Colangelo, M.A.; Bozzeda, F.; Heurtefeux, H.; Ondiviela, B.; Ostrowski, R.; Recio, M.; et al. Shifting sands? Coastal protection by sand banks, beaches and dunes. *Coast. Eng.* **2014**, *87*, 136–146. [CrossRef]
16. Cooper, J.A.G.; Jackson, D.W.T. Coasts in Peril? A Shoreline Health Perspective. *Front. Earth Sci.* **2019**, *7*, 260. [CrossRef]
17. French, J.; Payo, A.; Murray, B.; Orford, J.; Eliot, M.; Cowell, P. Appropriate complexity for the prediction of coastal and estuarine geomorphic behaviour at decadal to centennial scales. *Geomorphology* **2016**, *256*, 3–16. [CrossRef]
18. Vitousek, S.; Barnard, P.L.; Limber, P. Can beaches survive climate change? *J. Geophys. Res.–Earth Surf.* **2017**, *122*, 1060–1067. [CrossRef]
19. Charrua, A.B.; Bandeira, S.O.; Catarino, S.; Cabral, P.; Romeiras, M.M. Assessment of the vulnerability of coastal mangrove ecosystems in Mozambique. *Ocean Coast. Manag.* **2020**, *189*, 105145. [CrossRef]
20. Knight, J.; Burningham, H. The morphodynamics of transverse dunes on the coast of South Africa. *Geo-Mar. Lett.* **2021**, *41*, 47. [CrossRef]
21. Pereira, C.; Coelho, C.; Ribeiro, A.; Fortunato, A.; Lopes, C.L.; Dias, J.M. Numerical modelling of shoreline evolution in the Aveiro coast, Portugal–climate change scenarios. *J. Coast. Res.* **2013**, *SI65*, 2161–2166. [CrossRef]
22. Hallin, C.; Larson, M.; Hanson, H. Simulating beach and dune evolution at decadal to centennial scale under rising sea levels. *PLoS ONE* **2019**, *14*, e0215651. [CrossRef]
23. Alvarez-Cuesta, M.; Toimil, A.; Losada, I.J. Modelling long-term shoreline evolution in highly anthropized coastal areas. Part 2: Assessing the response to climate change. *Coast. Eng.* **2012**, *168*, 103961. [CrossRef]
24. Chowdhury, P.; Lakku, N.K.G.; Lincoln, S.; Seelam, J.K.; Behera, M.R. Climate change and coastal morphodynamics: Interactions on regional scales. *Sci. Total Environ.* **2023**, *899*, 166432. [CrossRef] [PubMed]
25. Kemp, A.C.; Hill, T.D.; Vane, C.H.; Cahill, N.; Orton, P.M.; Talke, S.A.; Parnell, A.C.; Sanborn, K.; Hartig, E.K. Relative sea-level trends in New York City during the past 1500 years. *Holocene* **2017**, *27*, 1169–1186. [CrossRef]
26. Houston, J.R. Sea-level acceleration: Analysis of the world's high-quality tide gauges. *J. Coast. Res.* **2021**, *37*, 272–279. [CrossRef]
27. Needham, H.F.; Keim, B.D.; Sathiaraj, D. A review of tropical cyclone-generated storm surges: Global data sources, observations, and impacts. *Rev. Geophys.* **2015**, *53*, 545–591. [CrossRef]
28. Tous, M.; Zappa, G.; Romero, R.; Shaffrey, L.; Vidale, P.L. Projected changes in medicanes in the HadGEM3 N512 high-resolution global climate model. *Clim. Dyn.* **2016**, *47*, 1913–1924. [CrossRef]
29. Bertin, X.; Prouteau, E.; Letetrel, C. A significant increase in wave height in the North Atlantic Ocean over the 20th century. *Glob. Planet. Ch.* **2013**, *106*, 77–83. [CrossRef]
30. Aarnes, O.J.; Reistad, M.; Breivik, Ø.; Bitner-Gregersen, E.; Ingolf Eide, L.; Gramstad, O.; Magnusson, A.K.; Natvig, B.; Vanem, E. Projected changes in significant wave height toward the end of the 21st century: Northeast Atlantic. *J. Geophys. Res.–Oceans* **2017**, *122*, 3394–3403. [CrossRef]
31. Luijendijk, A.; Hagenaars, G.; Ranasinghe, R.; Baart, F.; Donchyts, G.; Aarninkhof, S. The State of the World's Beaches. *Sci. Rep.* **2018**, *8*, 6641. [CrossRef] [PubMed]
32. Nichols, C.R.; Wright, L.D.; Bainbridge, S.J.; Cosby, A.; Hénaff, A.; Loftis, J.D.; Cocquempot, L.; Katragadda, S.; Mendez, G.R.; Letortu, P.; et al. Collaborative Science to Enhance Coastal Resilience and Adaptation. *Front. Mar. Sci.* **2019**, *6*, 404. [CrossRef]
33. Gräwe, U.; Wolff, J.-O.; Ribbe, J. Impact of climate variability on an east Australian bay. *Estuar. Coast. Shelf Sci.* **2010**, *86*, 247–257. [CrossRef]
34. Knight, J.; Harrison, S. Evaluating the impacts of global warming on geomorphological systems. *Ambio* **2012**, *41*, 206–210. [CrossRef]

35. Hoffmann, T. Sediment residence time and connectivity in non-equilibrium and transient geomorphic systems. *Earth-Sci. Rev.* **2013**, *150*, 609–627. [CrossRef]
36. Brown, J.M.; Prime, T.; Phelps, J.J.C.; Barkwith, A.; Hurst, M.D.; Ellis, M.A.; Masselink, G.; Plater, A.J. Spatio-temporal Variability in the Tipping Points of Coastal Defense. *J. Coast. Res.* **2016**, *SI75*, 1042–1046. [CrossRef]
37. Brunsden, D.; Thornes, J.B. Landscape Sensitivity and Change. *Trans. Inst. Br. Geogr.* **1979**, *4*, 463–484. [CrossRef]
38. Aagaard, T.; Davidson-Arnott, R.; Greenwood, B.; Nielsen, J. Sediment supply from shoreface to dunes: Linking sediment transport measurements and long-term morphological evolution. *Geomorphology* **2004**, *60*, 205–224. [CrossRef]
39. Short, A.D. Australia beach systems–The morphodynamics of wave through tide-dominated beach-dune systems. *J. Coast. Res.* **2003**, *SI35*, 7–20.
40. Knight, J.; Burningham, H. A morphological classification of coastal forelands, with examples from South Africa. *Geomorphology* **2022**, *415*, 108410. [CrossRef]
41. Brodie, K.; Conery, I.; Cohn, N.; Spore, N.; Palmsten, M. Spatial Variability of Coastal Foredune Evolution, Part A: Timescales of Months to Years. *J. Mar. Sci. Eng.* **2019**, *7*, 124. [CrossRef]
42. Cooper, N.J.; Hooke, J.M.; Bray, M.J. Predicting coastal evolution using a sediment budget approach: A case study from southern England. *Ocean Coast. Manag.* **2001**, *44*, 711–728. [CrossRef]
43. Rosati, J.D. Concepts in sediment budgets. *J. Coast. Res.* **2005**, *21*, 307–322. [CrossRef]
44. Short, A.D. Sediment transport around Australia—Sources, mechanisms, rates, and barrier forms. *J. Coast. Res.* **2010**, *26*, 395–402. [CrossRef]
45. Danladi, I.B.; Gül, M.; Ateş, E. Response of the barrier island coastal region of southwestern Nigeria to climate and non-climate forcing. *Afr. J. Mar. Sci.* **2020**, *42*, 43–51. [CrossRef]
46. Allen, T.R.; Oertel, G.F.; Gares, P.A. Mapping coastal morphodynamics with geospatial techniques, Cape Henry, Virginia, USA. *Geomorphology* **2012**, *137*, 138–149. [CrossRef]
47. Gupta, E.; Rajani, M.B. Historical coastal maps: Importance and challenges in their use in studying coastal geomorphology. *J. Coast. Conserv.* **2020**, *24*, 24. [CrossRef]
48. Mao, Y.; Harris, D.L.; Xie, Z.; Phinn, S. Global coastal geomorphology—Integrating earth observation and geospatial data. *Remote Sens. Environ.* **2022**, *278*, 113082. [CrossRef]
49. Kennedy, D.M.; Coombes, M.A.; Mottershead, D.N. The temporal and spatial scales of rocky coast geomorphology: A commentary. *Earth Surf. Proc. Landf.* **2017**, *42*, 1597–1600. [CrossRef]
50. Hapke, C.J.; Kratzmann, M.G.; Himmelstoss, E.A. Geomorphic and human influence on large-scale coastal change. *Geomorphology* **2013**, *199*, 160–170. [CrossRef]
51. Rosa-Santos, P.; Veloso-Gomes, F.; Taveira-Pinto, F.; Silva, R.; Pais-Barbosa, J. Evolution of coastal works in Portugal and their interference with local morphodynamics. *J. Coast. Res.* **2009**, *SI56*, 757–761.
52. Hamin, E.M.; Abunnasr, Y.; Dilthey, M.R.; Judge, P.K.; Kenney, M.A.; Kirshen, P.; Sheahan, T.C.; DeGroot, D.J.; Ryan, R.L.; McAdoo, B.G.; et al. Pathways to Coastal Resiliency: The Adaptive Gradients Framework. *Sustainability* **2018**, *10*, 2629. [CrossRef]
53. Masselink, G.; Lazarus, E.D. Defining Coastal Resilience. *Water* **2019**, *11*, 2587. [CrossRef]
54. Martínez, M.L.; Taramelli, A.; Silva, R. Resistance and resilience: Facing the multidimensional challenges in coastal areas. *J. Coast. Res.* **2017**, *SI77*, 1–6. [CrossRef]
55. Rust, I.C.; Illenberger, W.K. Coastal dunes: Sensitive or not? *Landsc. Urban Plan.* **1996**, *34*, 165–169. [CrossRef]
56. Eichmanns, C.; Lechthaler, S.; Zander, W.; Pérez, M.V.; Blum, H.; Thorenz, F.; Schüttrumpf, H. Sand Trapping Fences as a Nature-Based Solution for Coastal Protection: An International Review with a Focus on Installations in Germany. *Environments* **2021**, *8*, 135. [CrossRef]
57. Itzkin, M.; Moore, L.J.; Ruggiero, P.; Hacker, S.D. The effect of sand fencing on the morphology of natural dune systems. *Geomorphology* **2020**, *352*, 106995. [CrossRef]
58. De Battisti, D. The resilience of coastal ecosystems: A functional trait-based perspective. *J. Ecol.* **2021**, *109*, 3133–3146. [CrossRef]
59. Kombiadou, K.; Costas, S.; Carrasco, A.R.; Plomaritis, T.A.; Ferreira, Ó.; Matias, A. Bridging the gap between resilience and geomorphology of complex coastal systems. *Earth-Sci. Rev.* **2019**, *198*, 102934. [CrossRef]
60. Floerl, O.; Atalah, J.; Bugnot, A.B.; Chandler, M.; Dafforn, K.A.; Floerl, L.; Zaiko, A.; Major, R. A global model to forecast coastal hardening and mitigate associated socioecological risks. *Nat. Sustain.* **2021**, *4*, 1060–1067. [CrossRef]
61. Angus, S.; Hansom, J.D. Enhancing the resilience of high-vulnerability, low-elevation coastal zones. *Ocean Coast. Manag.* **2021**, *200*, 105414. [CrossRef]
62. Lloyd, M.G.; Peel, D.; Duck, R.W. Towards a social–ecological resilience framework for coastal planning. *Land Use Pol.* **2013**, *30*, 925–933. [CrossRef]
63. De Jong, B.; Keijsers, J.G.S.; Riksen, M.J.P.M.; Krol, J.; Slim, P.A. Soft engineering vs. a dynamic approach in coastal dune management: A case study on the North Sea barrier island of Ameland, The Netherlands. *J. Coast. Res.* **2014**, *30*, 670–684.
64. 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. [CrossRef] [PubMed]
65. Della Bella, A.; Fantinato, E.; Scarton, F.; Buffa, G. Mediterranean developed coasts: What future for the foredune restoration? *J. Coast. Conserv.* **2021**, *25*, 49. [CrossRef]

66. Ruckelshaus, M.; Reguero, B.G.; Arkema, K.; Guerrero Compéan, R.; Weekes, K.; Bailey, A.; Silver, J. Harnessing new data technologies for nature-based solutions in assessing and managing risk in coastal zones. *Int. J. Disaster Risk Red.* **2020**, *51*, 101795. [CrossRef]
67. Saleh, F.; Weinstein, M.P. The role of nature-based infrastructure (NBI) in coastal resiliency planning: A literature review. *J. Environ. Manag.* **2016**, *183*, 1088–1098. [CrossRef] [PubMed]
68. Sutton-Grier, A.E.; Gittman, R.K.; Arkema, K.K.; Bennett, R.O.; Benoit, J.; Blitch, S.; Burks-Copes, K.A.; Colden, A.; Dausman, A.; DeAngelis, B.M.; et al. Investing in Natural and Nature-Based Infrastructure: Building Better Along Our Coasts. *Sustainability* **2018**, *10*, 523. [CrossRef]
69. Pontee, N.; Narayan, S.; Beck, M.W.; Hosking, A.H. Nature-based solutions: Lessons from around the world. *Marit. Eng.* **2016**, *169*, 29–36. [CrossRef]
70. Orchard, S.; Schiel, D.R. Enabling nature-based solutions for climate change on a peri-urban sandspit in Christchurch, New Zealand. *Reg. Environ. Chang* **2021**, *21*, 66. [CrossRef]
71. Cohn, J.L.; Copp Franz, S.; Mandel, R.H.; Nack, C.C.; Brainard, A.S.; Eallonardo, A.; Magar, V. Strategies to work towards long-term sustainability and resiliency of nature-based solutions in coastal environments: A review and case studies. *Integr. Environ. Assess. Manag.* **2022**, *18*, 123–134. [CrossRef] [PubMed]
72. Van Coppenolle, R.; Temmerman, S. A global exploration of tidal wetland creation for nature-based flood risk mitigation in coastal cities. *Estuar. Coast. Shelf Sci.* **2019**, *226*, 106262. [CrossRef]
73. Aiken, C.M.; Mulloy, R.; Dwane, G.; Jackson, E.L. Working with Nature Approaches for the Creation of Soft Intertidal Habitats. *Front. Ecol. Evol.* **2021**, *9*, 682349. [CrossRef]
74. Gijsman, R.; Horstman, E.M.; van der Wal, D.; Friess, D.A.; Swales, A.; Wijnberg, K.M. Nature-Based Engineering: A Review on Reducing Coastal Flood Risk with Mangroves. *Front. Mar. Sci.* **2021**, *8*, 702412. [CrossRef]
75. Knight, J.; Burningham, H. Sand dunes and ventifacts on the coast of South Africa. *Aeolian Res.* **2019**, *37*, 44–58. [CrossRef]
76. Liu, Z.; Fagherazzi, S.; Cui, B. Success of coastal wetlands restoration is driven by sediment availability. *Comm. Earth Environ.* **2021**, *2*, 44. [CrossRef]
77. Ruckelshaus, M.H.; Guannel, G.; Arkema, K.; Verutes, G.; Griffin, R.; Guerry, A.; Silver, J.; Faries, J.; Brenner, J.; Rosenthal, A. Evaluating the Benefits of Green Infrastructure for Coastal Areas: Location, Location, Location. *Coast. Manag.* **2016**, *44*, 504–516. [CrossRef]
78. Keesstra, S.; Nunes, J.; Novara, A.; Finger, D.; Avelar, D.; Kalantari, Z.; Cerdà, A. The superior effect of nature based solutions in land management for enhancing ecosystem services. *Sci. Total Environ.* **2018**, *610–611*, 997–1009. [CrossRef]
79. Nelson, D.R.; Bledsoe, B.P.; Ferreira, S.; Nibbelink, N.P. Challenges to realizing the potential of nature-based solutions. *Curr. Opin. Environ. Sustain.* **2020**, *45*, 49–55. [CrossRef]
80. Bongarts Lebbe, T.; Rey-Valette, H.; Chaumillon, É.; Camus, G.; Almar, R.; Cazenave, A.; Claudet, J.; Rocle, N.; Meur-Férec, C.; Viard, F.; et al. Designing Coastal Adaptation Strategies to Tackle Sea Level Rise. *Front. Mar. Sci.* **2021**, *8*, 740602. [CrossRef]
81. Kumar, P.; Debele, S.E.; Sahani, J.; Rawat, N.; Marti-Cardona, B.; Alfieri, S.M.; Basu, B.; Basu, A.S.; Bowyer, P.; Charizopoulos, N.; et al. An overview of monitoring methods for assessing the performance of nature-based solutions against natural hazards. *Earth-Sci. Rev.* **2021**, *217*, 103603. [CrossRef]
82. Davis, J.; Whitfield, P.; Szimanski, D.; Golden, B.R.; Whitbeck, M.; Gailani, J.; Herman, B.; Tritinger, A.; Dillon, S.C.; King, J. A framework for evaluating island restoration performance: A case study from the Chesapeake Bay. *Integr. Environ. Assess. Manag.* **2022**, *18*, 42–48. [CrossRef] [PubMed]
83. Monteiro, R.; Ferreira, J.C. Green Infrastructure Planning as a Climate Change and Risk Adaptation Tool in Coastal Urban Areas. *J. Coast. Res.* **2020**, *SI95*, 889–893. [CrossRef]
84. Sohn, W.; Bae, J.; Newman, G. Green infrastructure for coastal flood protection: The longitudinal impacts of green infrastructure patterns on flood damage. *Appl. Geogr.* **2021**, *135*, 102565. [CrossRef] [PubMed]
85. McKenna, J.; MacLeod, M.; Power, J.; Cooper, A. *Rural Beach Management: A Good Practice Guide*; Donegal County Council: Lifford, Ireland, 2000.
86. Berry, A.J.; Fahey, S.; Meyers, N. Boulderdash and beachwalls–The erosion of sandy beach ecosystem resilience. *Ocean Coast. Manag.* **2014**, *96*, 104–111. [CrossRef]
87. Griggs, G.; Patsch, K. The protection/hardening of California's coast: Times are changing. *J. Coast. Res.* **2019**, *35*, 1051–1061. [CrossRef]
88. Areizaga, J.; Sanò, M.; Medina, R.; Juanes, J. Improving public engagement in ICZM: A practical approach. *J. Environ. Manag.* **2012**, *109*, 123–135. [CrossRef]
89. de Alencar, N.M.P.; Le Tissier, M.; Paterson, S.K.; Newton, A. Circles of Coastal Sustainability: A Framework for Coastal Management. *Sustainability* **2020**, *12*, 4886. [CrossRef]