Nature-Based Solutions in Coastal and Estuarine Areas of Europe

Roberta P. L. Moraes[1]*, Borja G. Reguero[2], Inés Mazarrasa[3], Max Ricker[4] and José A. Juanes[3]

[1]Research Centre for Experimental Marine Biology and Biotechnology PiE, University of the Basque Country UPV/EHU, Plentzia, Spain, [2]Institute of Marine Sciences, University of California, Santa Cruz, Santa Cruz, Spain, [3]IHCantabria—Instituto de Hidráulica Ambiental de la Universidad de Cantabria, Parque Científico y Tecnológico de Cantabria (PCTCAN) C/ Isabel Torres, Santander, Spain, [4]The Nature Conservancy in Europe gGmbH, Berlin, Germany

Momentum for sustainable and climate resilience solutions for coastal protection are growing globally given the pressing need to prevent further loss of biodiversity and ecosystems while meeting the climate change adaptation and mitigation goals. Nature-Based Solutions (NbS) represent an opportunity to align environmental and resilience goals, at a time of strained budgets in a global context and when short-term needs may run counter to long-term goals. In Europe, NbS fit the mandates of major EU environmental and climate change policies by restoring biodiversity and enhancing climate-resilience and carbon sequestration. Previous studies have compiled scientific evidence about hydro-meteorological hazards for the use of NbS. However, their implementation at scale is still lacking. As the knowledge and experience with NbS for adaptation to natural hazards and climate change increases, it becomes more important to draw lessons learned and insights for replicating and scaling up NbS, especially in coastal areas where their implementation is still limited compared to other environments. This study analyzed NbS case studies across European coastal and estuarine areas to draw key lessons, understand better the current status of implementation, and identify key challenges and gaps. From a total of 59 NbS case studies associated with flooding, erosion and biodiversity loss, results show an increase in NbS implementation since 1990s, but most rapidly between 2005 and 2015. Most of the case studies are hybrid solutions employing wetlands, predominantly located in the United Kingdom (UK) and the Netherlands. Funding of NbS is largely from public sources, and rarely come from a single or a private source. Three-quarters of the case studies reported monitoring activities, but more than half did not disclose quantitative results related to effectiveness against flooding and/or erosion. The need to improve coastal defenses was indicated as the main motivation for NbS implementation over traditional structures, while sustainability was the most mentioned additional reason. Although a variety of co-benefits and lessons learned was identified, clearer descriptions and enhanced details of such information are required. There is a need for tools and strategies to expand knowledge sharing of lessons learned to enable further replication of successful cases in other areas.

Keywords: nature-based solutions, coastal, estuarine, climate adaptation, coastal protection, sustainability, natural infrastructure, Europe

INTRODUCTION

The impacts of climate change in coastal areas concern a significant part of society given that a large fraction of the global population (41%) and world's megacities (60%) are located in the coastal zone (Martínez et al., 2007). Coastal areas combine high population density, concentration of economic activities (Creel 2003), and high exposure to the impacts of waves, extreme sea levels, runoff, land subsidence and other hazards (Lee et al., 2021). Sea Level Rise (SLR) and impacts from extreme weather events will be most felt in most coastal areas in the next decades (Oppenheimer et al., 2019) where 190–630 million people are predicted to be inundated by 2,100 (Kulp and Strauss 2019). Coastal flood risk is likely to increase due to expected strengthening of storm intensity, accelerated SLR and land subsidence (Reguero et al., 2015; Syvitski et al., 2009; Temmerman et al., 2013; Lin et al., 2012).

In Europe, nearly half of the population lives less than 50 km from the sea (Statistical Office of the European Communities, 2011) and many coastal regions are already experiencing the impacts and costs of climate change and coastal hazards (Masselink et al., 2016; Ganguli and Merz 2019; Madsen, Mikkelsen, and Blok 2019). Most European countries are expected to be affected by frequent flooding events and SLR over the upcoming decades (European Environment Agency, 2019). For example, in the United Kingdom (UK), people exposed to a relevant annual likelihood of coastal flooding would increase between 37% and 178% due to SLR (Edwards 2017). Impacts from coastal flooding across continental Europe are also projected to increase significantly with rising sea levels (Vousdoukas et al., 2018), but increased climate hazards will coincide with an expected increase in population living in coastal areas, by one estimate of 355 million people by 2035 (Maul and Duedall 2019).

The traditional coastal protection approach has relied on 'hard' engineering solutions that are unlikely to withstand the increasing pressure from intensified hydrometeorological hazards caused by climate change (Kumar et al., 2020). Moreover, the maintenance costs of such structures could become unfeasible (Morris et al., 2018). Therefore, the need of lower cost, sustainable and resilient solutions is increasing. In this context, Nature-based Solutions (NbS) are emerging globally as a strategy that employ natural features to address hazards while enhancing biodiversity (EC 2021b). NbS may include actions to protect, sustainably manage and restore natural or modified ecosystems that provide critical ecosystem services for human well-being and biodiversity (Cohen-Shacham et al., 2016). NbS leverage the hazard mitigation properties of natural ecosystems. In coastal environments, ecosystems such as dunes, seagrass meadows, saltmarshes and biogenic reefs (e.g., oyster reefs) are able to protect coastal areas from erosion and flooding by dissipating the hydrodynamic energy through their submerged canopies or structural complexity (Gedan et al., 2011; Temmerman et al., 2013; Hanley et al., 2014; Ondiviela et al., 2014). Unlike "hard" engineering structures, coastal vegetated ecosystems and biogenic reefs can self-adapt to sea level rise through different mechanisms. Vegetated ecosystems are able to enhance soil vertical accretion and soil elevation due to the accumulation of large belowground biomass and the trapping of particles from the water column (Duarte et al., 2013; Kirwan and Megonigal 2013; Potouroglou et al., 2017). Oyster reefs grow vertically through attracting oyster larvae that drift through the water and latch onto the existing wall, contributing to its growing (Rodriguez et al., 2014). In addition, coastal habitats provide multiple other ecosystem services relevant to coastal communities, such as fisheries support, biodiversity, water quality improvement, and recreational and cultural benefits (Barbier et al., 2011). In the case of vegetated ecosystems, they are also significant carbon sinks due to their high productivity and their high carbon burial capacity (Mcleod et al., 2011), playing a significant role in climate change mitigation (Nellemann et al., 2009; Serrano et al., 2019).

In Europe, the European Commission (EC) is devoting great efforts in supporting NbS to address climate change and other environmental challenges (EC, 2015). For instance, the European Green Deal, a roadmap to make the EU's economy sustainable, places NbS at the center of climate adaptation and mitigation and highlights their role in ensuring healthy and resilient seas and oceans. Moreover, the implementation of NbS is also supported by different European policies, such as The Green Infrastructure Strategy (EC, 2021a), the EU Strategy on Adaptation to Climate Change (EC, 2013) or the Floods Directive (2007/60/EC). In addition to the policy framework, the EC has invested substantial financial resources in NbS dissemination, which resulted in the creation of several integrative platforms aiming to support the replication, upscaling and dissemination of NbS (Faivre et al., 2017; Kumar et al., 2020).

The application of NbS to mitigate and adapt to climate change in coastal and estuarine areas also provides an opportunity to restore and maintain coastal ecosystems in Europe, which have been historically threatened and transformed by human activities with an estimated reduction in their original surface of 2/3 for coastal wetlands (Airoldi and Beck 2007). The destruction of coastal ecosystems leads to the loss of all ecosystem services provided, including the role these ecosystems play in coastal protection against climate change hazards (Vo et al., 2012). The application of NbS can lead to the recovery and maintenance of biodiversity and all other coastal ecosystems services provided to societies (Faivre et al., 2017), while contributing to meet the goals of other conservation policies (e.g., EU Habitats directive; EU Birds Directive; Esteves 2014).

Despite the policy tailwinds, the application of NbS for coastal protection is still scarce compared to traditional engineered options in most of countries worldwide, including Europe (Morris et al., 2018). Major barriers for the wider implementation of NbS are the difficulty to predict its long-term effectiveness, the lack of standardized methods to assess efficacy, and a lack of data to produce cost-benefit analysis, especially when compared to traditional engineering approaches (Temmerman et al., 2013; Narayan et al., 2016; Morris et al., 2018). NbS in the context of hydrometeorological hazards has been the focus of extensive research during the last decade (e.g., Arkema et al., 2017; Faivre et al., 2017; Debele et al., 2019; Kumar et al., 2020; Kopsieker et al., 2021). However, Ruangpan et al. (2020) found that only 6% of the

TABLE 1 | Characteristics of the main NbS platforms reviewed in this study, including a short description and purpose of each database and the main features and shortcomings identified, pertinent to this study.

Platform and source	Description and purpose of the platform	Main features	Shortcomings
EcoShape—building with nature	- Consortium formed by 15 parties to promote Building with Nature EcoShape (2020) - Aims to provide guidelines for reproduction of NbS through pilot projects and its respective monitoring results	- Comprehensive content - Data efficiently structure per phase (Overview, Initiation, Planning and design, Construction, Operation and maintenance, Lessons learned)	- Filters are limited to landscapes and technology readiness levels - Lessons learned categories are not standardized between different pilot projects
OPPLA	- Joint output of OPERAs and OpenNESS projects with over 60 contributors OPPLA (2021) - EU collection of NbS case studies - Clear approach to knowledge sharing to a wide audience	- User-friendly interactive map - Standardized structure including available data per section - Keywords inside project's description can be used to search for similar projects	- A few projects provided conflicting information between listed references - Filters limited to scale and type
OURCOAST—ICZM in Europe	- 3-year program dedicated to knowledge sharing around coastal planning and management EC (2012) - Specific focus given to adaptation to climate change, communication systems and planning instruments	- Lessons learned are available - Includes associated costs - Database encompasses a variety of countries - Diversity of police-making initiatives	- Interactive database was discontinued - Access to database seem secluded - Database not very user-friendly
The River Restoration Center (RRC)	- UK's expert center in river restoration, habitat improvement and catchment management the RRC (2014a) - Part of the National River Restoration Inventory (NRRI) the RRC (2014b) - Propagates expertise and provides site-specific technical advice	- Comprehensive structure with standard fields in a PDF format - Contains section dedicated to effectiveness and project's costs - Variety of filters available - Anyone may submit their projects (posted after the RRC's review)	- Lessons learned mostly technical/engineering-related - Contains only historical data up to 2017 for projects in the UK the RRC (2014c)
RESTORE (RiverWiki)	- Main deliverable of the EU LIFE + RESTORE project the RRC (2014b) - Part of the NRRI the RRC (2014b) - Currently funded by the EA and maintained by the RRC RESTORE (2014)	- User-friendly platform with Wikipedia-like structure - Anyone may submit their projects (posted after the RRC's review) - Global database integrated with the RRC's UK	- Search for case studies might be complicated depending on purpose of search
NATURVATION	- 4-year project focused on building expertise around NbS in urban areas NATURVATION (2017a) - Developed by 14 different institutions in the EU	- Resourceful interactive map - Innovative filters including key challenges, urban setting and project cost NATURVATION (2017b)	- Limited fields and sections - Data was collected between June and August of 2017 and it has not been further updated NATURVATION (2017a)
Climate ADAPT	- Cooperation between the European Commission and the European Environment Agency (EEA) Climate-ADAPT (2020b) - Focused on knowledge sharing about adaptation policies to address climate change-related issues European Environment Agency (2018)	- Complete and standardized project descriptions - Indicates point of contact for each project - Up to date platform - Broad filtering options including type of climate impact and funding Climate-ADAPT (2021a)	- Lack of quantitative data showing effectiveness

analyzed NbS publications between 2007 and 2019 were associated with coastal flooding, and there are even fewer publications presenting data analyzing the success of implemented NbS projects in coastal areas, particularly at a local scale.

The capitalization of results and lessons learnt from previous projects can contribute to overcome key gaps of knowledge and support the replication and improvement of future ecosystem-based projects. This study investigates the application of NbS for coastal climate change adaptation in Europe, based on a detailed review of 59 implemented NbS case studies across European countries. We aim to identify the prevailing characteristics amongst case studies, including the main motivation that triggered the choice of a NbS over a traditional coastal protection approach and the reported co-benefits. Unlike previous reviews, our focus is on case studies information through the review of integrative platforms. Successful examples may include helpful technical details for replication. The analysis leads to the presentation and discussion of identified lessons learned from our selected sample.

TABLE 2 | Design characteristics (left) and classification per characteristic (right).

Design characteristics	Classification
System type	Estuarine; Coastal; River basin
Type of location	Urban; Rural/suburban
Type of infrastructure	Green; Hybrid
Coastal challenge addressed	Reduce flooding; Reduce erosion; Biodiversity restoration/conservation; Reduce flooding and erosion
Type of intervention	Ecosystem creation; Ecosystem restoration; Managed realignment
Ecosystem used	Natural embankments; Wetlands; Salt marshes; Oyster reefs; Beach and dune systems

MATERIALS AND METHODS

Case Studies Compilation

This study analyzed seven platforms (available up to November 2020) that collected information on NbS case studies for climate change hazards in coastal areas in Europe (**Table 1**): EcoShape, OPPLA, OURCOAST, The River Restoration Center, RESTORE (RiverWiki), NATURVATION and Climate-ADAPT. From these sources, we selected case studies that met at least one of the three criteria: 1) the use of ecosystem services was an integral part of the design rationale, 2) it included ecosystem restoration activities such as the removal of engineered solutions or the combination of traditional engineering with the use of ecosystems, and/or 3) it resulted in the creation of new habitats that could provide flood or erosion benefits as well as other ecosystem services. All the case studies we selected were aimed at coastal adaptation to hydrometeorological hazards, either directly (challenge addressed) or indirectly (as a co-benefit). The information from these knowledge sharing platforms was complemented with searches in Google Scholar to gather more information, whenever available, about the case studies listed in the initial search. In total, we collected 59 case studies, which resulted from case studies that met the aforementioned criteria and provided on all relevant design characteristics (**Table 2**). The complete database of case studies is available in the supplementary information (**Supplementary Table S1**).

Variables of Interest

The design characteristics of our case studies selection ($n = 59$) describe the focus of the project and include system type, type of location, type of infrastructure, coastal challenge addressed, type of intervention and ecosystem used, and each design characteristic contained at least two classes (**Table 2**). The system typologies considered were estuarine, coastal and river basin case studies. The "river basin" type refers to projects that encompass a larger area than the estuarine region and could not be considered "estuarine." Coastal projects cover only the open coastal zone (e.g., beaches and sand dunes systems). The type of locations considered were urban, and non-urban/non-populated, which refers to low-density or uninhabited areas. This classification was based on visual analysis of satellite imagery. The type of infrastructure was classified as: green, when no construction or realignment of engineered coastal defenses is implemented; or hybrid interventions, when ecosystem services were combined with "hard" engineering structures.

The types of funding were classified into public, private, Private-Public Partnership (PPP) or other types of funding. The latest includes trust funds of various structures (e.g., lottery funds, public and private donations), charity contributions, and taxation schemes. In addition, we analyzed the predominant funding sources in the countries where NbS case studies were more frequent. Regarding the information compiled about project monitoring, we registered whether or not monitoring of the case study was conducted. Later, we specifically assessed whether flood and/or erosion effectiveness were indicated by variables such as return periods and accretion rates, respectively.

Information on the "motivation" for the case studies was also revised, especially when the source indicated the motivation for choosing NbS over a traditional approach. The motivation was considered as the goal that would have not been achieved without the NbS component when compared to a traditional solution. For example, if the project goals were environmental compensation and flood protection, the main motivation is registered as environmental compensation because this would not have been achieved by implementing a traditional coastal protection scheme. At least one main motivation was identified per project, and, in the cases where other reasons for choosing NbS were mentioned in the project description as key factors, they were classified as additional reasons. Motivations were grouped in different categories: 1) sustainability, 2) policy-making context, 3) recreation and tourism, 4) cost-benefit relationship, 5) environmental compensation, 6) coastal defense improvement, and 7) development of expertise and knowledge sharing. Each motivation category is described in **Supplementary Table S2**.

Some projects reported co-benefits derived from the implementation of NbS, which were registered and grouped into 13 different categories: 1) biodiversity conservation and restoration, including bird and fish protection; 2) recreation; 3) tourism; 4) reduction of flooding; 5) reduction of erosion; 6) community awareness of coastal and estuarine environments; 7) economic benefits; 8) water quality improvement; 9) educational gains; 10) cost reduction; 11) area availability for housing; 12) navigation; and 13) air quality. Sustainability was considered an intrinsic value to NbS; thus, it was not listed as a co-benefit.

When reported, lessons learned were registered and classified into 10 categories: 1) communication, 2) cost-benefit analysis, 3) funding and costs, 4) planning, design and construction, 5) permitting and legal requirements, 6) biological and ecological, 7) physical, 8) monitoring and maintenance, 9) management, and

FIGURE 1 | Temporal and spatial distribution of NbS case studies in Europe, shown by **(A)** the cumulative number of projects implemented per year and **(B)** a map of the European continent.
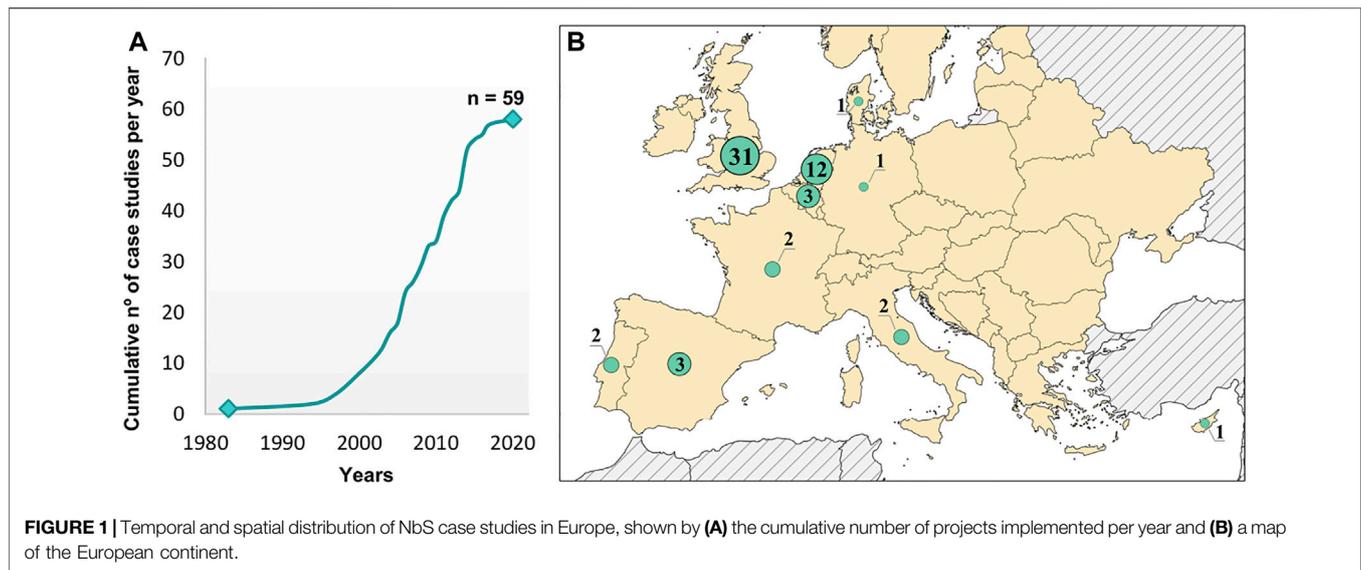
10) stakeholder engagement. A detailed description of each category is presented in **Supplementary Table S3**.

RESULTS

Implementation Status of Coastal Nature-Based Solutions in Europe

From the 59 projects reviewed, most of the projects were implemented from 2002 to present-time; only one was implemented in the 1980s and two in the 1990s. More specifically, the implementation of projects significantly raised between the years 2005 and 2015 (**Figure 1A**). The projects analyzed show a clear regional concentration: nearly 73% ($n = 43$) of the case studies were located in two countries, the United Kingdom (53%, $n = 31$) and the Netherlands (20%, $n = 12$), whereas the other projects were distributed among Belgium and Spain (5% each, $n = 3$), Portugal, Italy and France (3% each, $n = 2$), and Germany, Cyprus and Denmark (2% each, $n = 1$) (**Figure 1B**). Only one of the case studies was a transnational project between Belgium and the Netherlands (not indicated in **Figure 1B**).

Figure 2 provides a summary of the main characteristics of the case studies reviewed. More than half of the projects (69%, $n = 41$) indicated that coastal protection (reduction of flooding and/or erosion) was the main challenge. Biodiversity restoration and/or conservation was indicated as the main challenge addressed in the remaining 18 projects (31%). More than half of the interventions (61%, $n = 36$) employed ecosystem restoration, while the other 39% was almost equally split between ecosystem creation (19%, $n = 11$) and managed realignment (20%, $n = 12$). Wetlands accounted for 56% of the case studies ($n = 33$), from which 32% ($n = 19$) were described as salt marshes and 24% ($n = 14$) were generally presented as wetlands.

Most of the case studies (64%, $n = 38$) were considered coastal, and almost one-third (31%, $n = 18$) were implemented in

estuarine areas. Only three cases were described as river basin systems since they cover the estuarine transition to riverine areas, although still tidally-influenced, and are not limited to coastal or estuarine zones (e.g., the "River as Tidal Park" case study in the Netherlands). More than half of the case studies were implemented in urban areas (54%, $n = 32$) compared to 27 in non-urban areas (46%). The type of infrastructure employed shows a predominance of hybrid solutions (64%, $n = 38$) over solely nature-based ones (36%, $n = 21$).

Most of the projects had more than one funding source and it is important to highlight that the same sponsor may have contributed to more than one project (number of contributions exceeds the amount of funding sources). Only 15 projects (25%) reported to have only one source of funding; 36 projects (61%) reported more than one funding source; and eight reported no funding information (14%). It was not possible to identify all the funding sources for each project that indicated more than one sponsor. In total, 130 contributions to NbS case studies were identified from 72 different funding sources. The results indicate a major prevalence of public funding amongst the contributions to case studies (77%, $n = 99$), while other types of funding represented 17% ($n = 22$). Only 6% were associated with contributions from private sources ($n = 8$), and PPP were also infrequent, representing only 1% ($n = 1$). Other funding mechanisms were only present in the UK and the Netherlands, representing 22% and 8% of the total contributions in each country, respectively. Among public sources, 85% of the projects were funded by local, regional or national governments, whereas only 15% were at least partially sponsored by the European Union through different instruments (e.g., LIFE program, INTERREG program and the Network for Europe grants).

Reportedly, 54 out of 59 case studies were completed or partially implemented, allowing monitoring activities. To assess the monitoring status, the total number of projects considered was $n = 54$. Amongst them, monitoring was declared in 81% of case studies ($n = 44$), but more than half did not present any information about flood (57%, $n = 31$) neither erosion effectiveness (56%, $n = 30$).
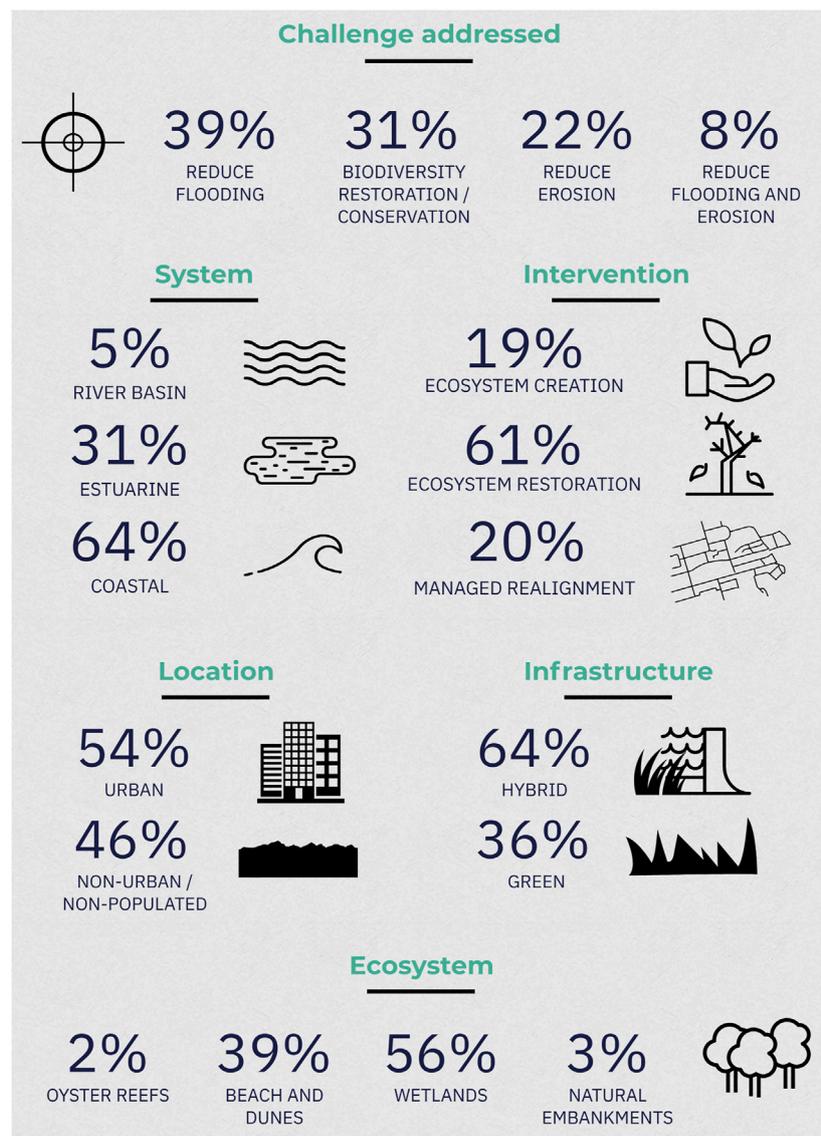
FIGURE 2 | Key characteristics of the review of NbS projects in coastal and estuarine areas in Europe (Infographic produced using Piktochart online tool - https://piktochart.com/).

Additionally, most of the reported monitoring results were related to biodiversity benefits (e.g., presence of water birds). Reported field measurements after implementation accounted for 43% (*n* = 23) of the case studies. Yet, fewer cases (35%, *n* = 19) provided detailed results evidencing effectiveness, such as accretion rates or the performance of a flood protection scheme after a storm surge event.

Motivation for Nature-Based Solutions Implementation

The main motivation for the implementation of most NbS case studies (24%, *n* = 14) was the need for improvement of existing coastal defenses (**Figure 3**). This motivation was also mentioned as an additional reason in 22% of the projects. Developing

expertise around NbS implementation and sharing such knowledge ranked second in the case study motivation (19%, *n* = 11), but it was not mentioned as an additional reason for implementation. "Sustainability" and "environmental compensation" were each cited as the main motivation in 15% of the case studies. "Sustainability" was the most mentioned as an additional reason (39% of the projects examined); however, the need to legally compensate for environmental losses which occurred elsewhere, as defined by Persson (2013), was not mentioned by any of the case studies as an additional reason. Moreover, it was not possible to assert whether when referring to sustainability as a key driver the project owners considered environmental justice and equity aspects as an influential design factor. These aspects should be further explored and

FIGURE 3 | Motivation for the implementation of NbS projects per category in terms of percentage.

FIGURE 4 | Frequency of co-benefits reported, per category.
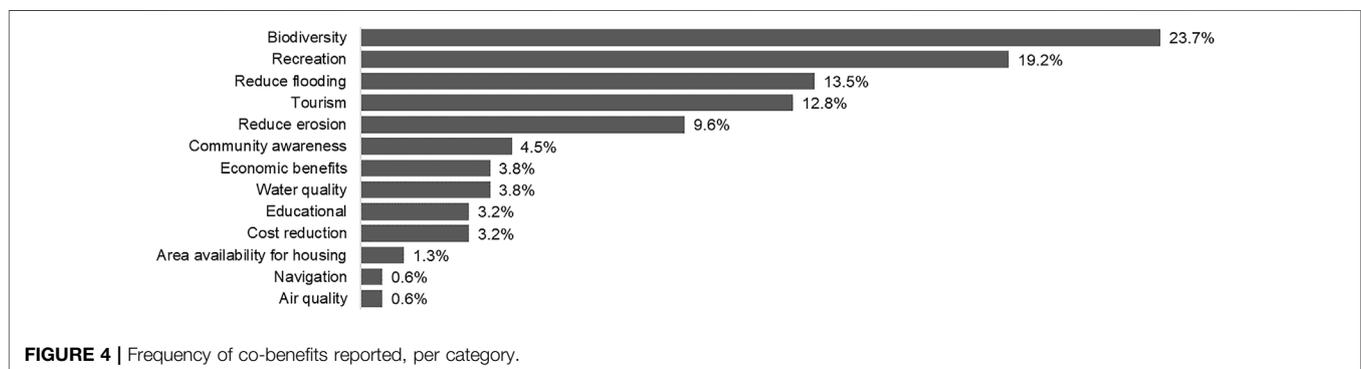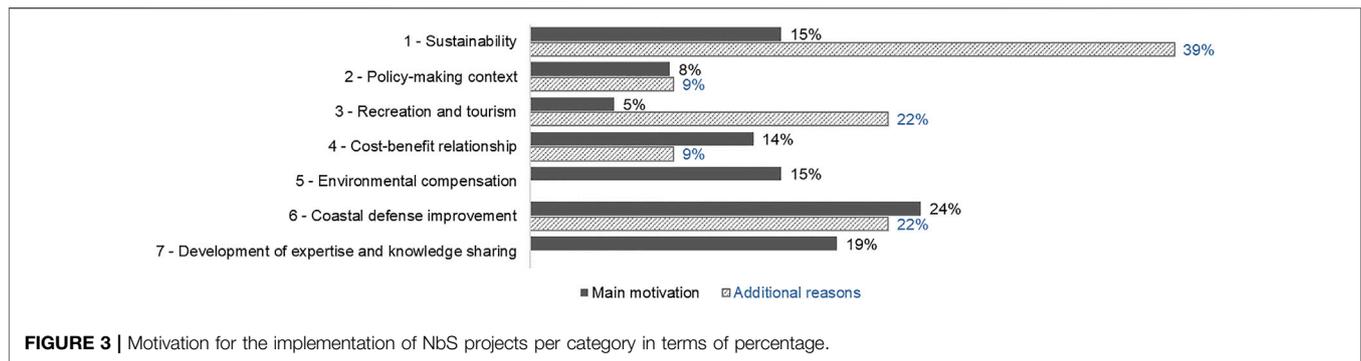
explicitly considered in future NbS. Compensation schemes were observed only in three countries: the UK ($n = 10$), representing 17% of the total number of case studies; the Netherlands (3%, $n = 2$); and France (2%, $n = 1$). The influence of the policy-making context was mentioned in 8% and 9% of the projects as main motivation and additional reason, respectively. Recreation and tourism were the least mentioned main motivation (5% of the projects); however, it was mentioned as an additional reason in 22% of projects.

Co-Benefits

A variety of additional benefits (i.e., co-benefits) were reported in the description of the projects. In total, 156 co-benefits were mentioned in the projects examined (**Figure 4**). Four categories of co-benefits represented more than half of the total reported co-benefits (69.2%, $n = 108$): biodiversity conservation, enhancement and restoration (23.7%, $n = 37$); recreation (19.2%, $n = 30$); reduce flooding (13.5%, $n = 21$); and tourism (12.8%, $n = 20$). Reduce flooding and reducing erosion (9.6%, $n = 15$) were considered a co-benefit when the challenge addressed was biodiversity restoration/conservation; only to reduce flooding; or only to reduce erosion. The least mentioned categories included: water quality improvement (3.8%, $n = 6$); economic benefits (3.8%, $n = 6$), which were mentioned when there were businesses at risk prior to project implementation; education (i.e., learning outcomes for the community and/or visitors; 3.2%, $n = 5$); cost reduction in comparison with traditional solutions (3.2%, $n = 5$); and area availability for the construction of houses (1.3%, $n = 2$). Some co-benefits were

uncommon and very particular to the case study, such as navigation enhancement resulting from sustainable dredging, and air quality improvement from less suspended solids (0.6% each).

Lessons Learned

In total, 155 different lessons learned were reported across all the case studies we reviewed, but many shared common features. Almost one out of four (23.2%, $n = 36$) of the lessons learned mentioned were associated with the importance of stakeholder engagement (**Figure 5**), including negative experiences of lack of engagement that resulted in project delays. For instance, the creation of a depoldered area between Belgium and the Netherlands as part of the Sigma Plan was delayed due to the opposition of landowners, requiring an improved stakeholder engagement strategy (Climate-ADAPT 2020a). On the other hand, the case study of the shellfish reefs placed in Eastern Scheldt for coastal protection showed the effectiveness of preparing a stakeholder engagement plan which employed a variety of communication methods to reach different interested parties. In 13.5% ($n = 21$) and 12.3% ($n = 19$) of the cases, the knowledge on biological and ecological, and physical site-specific aspects, respectively, were mentioned as essential and as a critical gap when unavailable. These lessons learned were generally associated with technical aspects for implementation. For example, the holistic understanding of physical processes affecting sediment transport were a key success factor in the Poole Bay Beach Replenishment Trial (Heron 2016). The relevance of a well-structured
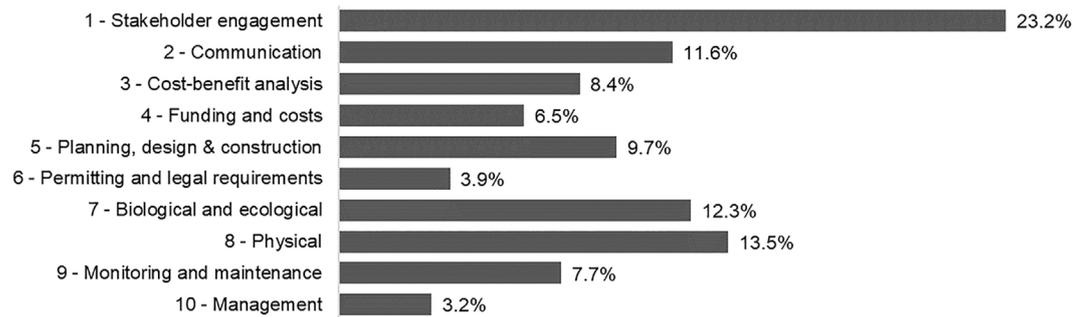
FIGURE 5 | Percentage of reported lessons learned per category defined for the project sample (=59).

communication framework was cited in 11.6% ($n = 18$) of the lessons learned reports, while optimized planning, design and construction were mentioned in 9.7% ($n = 15$) of the cases.

The less frequently reported lessons learned included the need for conducting cost-benefit analysis; meeting permitting and legal requirements and timetables; the importance to guarantee funding during the implementation phase; and relevance of resources for monitoring and maintenance (<9% each). The least mentioned was the need for project management experience and multidisciplinary team involved (3.2%, $n = 5$).

DISCUSSION

This study assesses the status and patterns of implementation of NbS for coastal defense in European countries based on a review of case studies that have been documented and reported in different public platforms in Europe with the aim to support the replication and improvement of future ecosystem-based projects. In comparison to previous reviews on NbS projects, mainly based on scientific literature (Morris et al., 2018; Ruangpan et al., 2020), this study is based on the review of projects implemented, independently of whether the projects delivered scientific outcomes or not, which may not be reflected in scientific articles. We focused on the analysis of a range of project characteristics critical for the implementation of NbS projects in order to support replication. This approach allows a comprehensive assessment on the status of implementation of NbS, not available in scientific studies.

We found that the number of projects implemented over the years has increased during the last decades demonstrating a growing interest in the implementation of NbS for coastal adaptation. In particular, the number of projects increased from 2005 onwards, coinciding with the raise in scientific publications about NbS found by Ruangpan et al., (2020). Yet, an unequal distribution of case studies among countries is perceived in our results, showing that most of the identified projects are located in two countries, the UK (53%) and the Netherlands (20%) whereas all the other eight countries in our database represent less than 5% of the projects. The higher number of NbS case studies in UK and the Netherlands is consistent to their need to respond to already high levels of

coastal erosion (Masselink and Russell, 2013) and exposure to flooding (van de Hurk et al., 2006), but it could also be result of further communication, advertisement and reporting of the case studies through regional platforms and other venues (i.e., information inequity). However, it is also likely that these two countries have more experience with coastal NbS given the challenges of flooding in the Netherlands (Jongejan and Maaskant, 2015), and long-established shoreline management plans and wetland compensation schemes in the UK (Doody, 2013). Nevertheless, future scenarios of climate change predict higher increase in the frequency of coastal flooding events in southern European countries (Oppenheimer et al., 2019, as cited in; European Environment Agency, 2019), including Portugal, Spain and Italy, when compared to UK and the Netherlands. These scenarios may justify further expansion of successful cases in southern Europe; yet, according to our results and those of previous studies, experience in southern Europe lags significantly behind in the implementation of coastal NbS.

Considering the substantial investments that the EU has made in NbS research (140 million euros between 2016 and 2017, for instance) (Faivre et al., 2017), reporting on implementation of adaptation measures and their effectiveness for coastal protection are still scarce (Narayan et al., 2016; López-Dóriga et al., 2020; Kumar et al., 2021). Although focusing on green urban infrastructure, Frantzeskaki (2019) has shown that design and scale of NbS directly affect the level of easiness in collecting effectiveness data, which can support replication. Nevertheless, each one of the integrative platforms (**Table 1**) include different information on projects and design characteristics, which limited the identification of projects to a total of 59. This could suggest that some standardization of information from implemented projects, and a joint platform under the EU Commission should help to expand and replicate successful NbS projects. There are also overlaps among the platforms that could be eliminated by integrating different initiatives.

However, replication of these cases should consider local settings and contexts. The effectiveness of NbS is highly associated with the site conditions, which might decrease the relevance of data collected in other locations if they are not carefully assessed and can hamper its replication (Arkema et al., 2017). For instance, water depth, sediment supply, tidal range and vegetation density are factors that affect NbS effectiveness and

must be verified in the field as they are site-specific (Pontee et al., 2016). Readily available effectiveness data on implemented small to mid-sized coastal NbS is still scarce, and projects are often lacking on clearly defined baselines that allow a realistic comparison between site conditions before and after the NbS project is executed (Brady and Boda, 2017; Chausson et al., 2020).

Although our results show that most projects are located in coastal areas, there is a lack of scientific papers published on NbS case studies in coastal areas, as indicated by Ruangpan et al. (2020). In addition, our review shows less implementation for some specific ecosystems, for example, oyster reefs compared to coastal wetlands, which is the most applied type of ecosystem. However, most of the coastal wetland NbS are in the UK given the importance of salt marshes in the country associated to habitat losses, land reclamation, coastal squeeze, and the long shoreline management planning that has occurred in the country (Garbutt, 2005; Brady and Boda, 2017; Environment Agency, 2021). Yet, there are also opportunities in other NbS in Europe, such as beach and dune systems (Doody, 2016), and their potential for coastal protection should be further developed and disseminated.

Funding of NbS is largely dominated by public sources with little participation of the private initiative. In the UK, trust funds are a common mechanism used to fund NbS; however, it is unclear why such mechanism is not widespread in the rest of the EU. According to Toxopeus and Polzin (2021), the challenges of combining private and public sources and the scarcity of methods to valuate NbS benefits are the main financial barriers to NbS projects. Whilst there are a number of studies estimating the value of ecosystem-services (e.g., King and Lester, 1995; Barbier et al., 2011; Menéndez et al., 2020; Zhu et al., 2020), economic assessments and financial models are still faulty (Seddon et al., 2020). Furthermore, the COVID-19 pandemic has affected the funding availability for climate adaptation initiatives as governments have committed resources to health and economic incentives (Global Center on Adaptation, 2021). On the other hand, the European Recovery and Resilience Facility will mobilize 724 billion euros to mitigate the economic and social impacts of the pandemic, but also represents an opportunity for a green and sustainable transition (EC 2021c). A minimum of 37% has been estimated for climate investments and reforms, where coastal NbS projects could also be included in support of the implementation of adaptation goals (EC 2021c). In Europe, efforts to tackle climate change challenges are incentivized by different policy frameworks such as the European Green Deal and funding mechanisms such as the EU LIFE sub-program on Climate change mitigation and adaptation. A green recovery highlights the importance of focusing resources on areas that would benefit the most from NbS; however, such mapping of priority areas is still insufficient (Van Coppenolle and Temmerman 2020).

Co-benefits should also be considered while mapping priority areas for NbS implementation. Most co-benefits in this review were related to biodiversity enhancement, which is linked to the most reported additional motivation ("sustainability"). Yet, there is a need to improve the assessment and reporting of other co-benefits, highly relevant for climate change adaptation and mitigation such as flood attenuation, shoreline accretion and carbon sequestration (Nellemann et al., 2009; Duarte et al., 2013). Also, the participation of stakeholders in the identification of co-benefits is vital to support public acceptance (Giordano et al., 2020), as NbS is still seen as an unusual approach by coastal communities (Anderson and Renaud 2021). Emphasis should be given to socio-economic effects arising from NbS implementation and the number of societal challenges that can be addressed by NbS in addition to coastal protection, such as physical and mental health assistance by providing functional green spaces and reduction of unemployment through the creation of green jobs (Davies et al., 2021; Kopsieker et al., 2021).

Based on our results, the case study main motivation was a combination of factors that led to the choice of a NbS project. For instance, the Medmerry Managed Realignment scheme was implemented due to the need to compensate environmental losses elsewhere in an area requiring increased levels of coastal protection; however, traditional structures were no longer financially feasible, and a cost-benefit analysis indicated the ecosystem-based approach as the preferred alternative. Yet, the need of coastal defense improvement was the most mentioned motivation. The explicit inclusion of, quantification of, and monitoring of sustainability is still largely absent from the write-ups and communication of many NbS projects in Europe. Based on this review, the inclusion of measures to monitor and quantify the sustainability of NbS in future projects, for example, through the use of Life Cycle Assessment, aligned with Sustainable Development Goals or the International Organization for Standardization's frameworks for social and environmental sustainability reporting (ISO 2021), should be included to provide metrics on sustainability of the approaches compared to other alternatives.

Our results indicate that hybrid solutions were preferred over the sole use of coastal ecosystems to address efficiency issues of coastal "hard" engineering. Benefits of employing hybrid solutions include reduced maintenance costs of existing structures, increasing the structure's lifespan and avoiding elevated capital costs to build new structures; positive socio-environmental results; and improved coastal protection against flooding (Pontee et al., 2016). The awareness of adverse effects resulting from coastal habitats destruction has increased the use of NbS for coastal protection, although the finer details of the how much protection NbS provides during storms are still insufficient. For example, the role of vegetation in attenuating waves are still not fully understood due to uncertainties associated with vegetation responses during storm conditions and the prediction of vegetation longevity caused by seasonal biomass variations (van Wesenbeeck et al., 2017; Bouma et al., 2014; as cited in; Morris et al., 2018).

The review also highlighted that the reported lessons learned were often poorly described and little detail was given about the implementation experiences. Stakeholder engagement was often mentioned as crucial for the project to guarantee public acceptance, which has been shown to be essential for the mainstreaming of NbS (Anderson and Renaud 2021). As illustrated by the Hesketh Out Marsh Managed Realignment (Climate-ADAPT, 2021b), the engagement of partners is

crucial to secure the financial resources required throughout the project, which explains the little amount of lessons learned reports on resources for monitoring and maintenance, assuming that guaranteeing funding for such purposes is considered a component of stakeholder participation. According to our results, vandalism and delays in implementation are amongst the issues caused by the disengagement of the community, which seems to be related to the lack of communication as the importance of a well-developed communication plan was also frequently highlighted. Although technical aspects of each case study might not be as replicable in other locations, sharing knowledge on issues and solutions with the wider public could be essential to help avoid previous mistakes and facilitate replication and implementation of NbS.

CONCLUSION AND RECOMMENDATIONS

As far as the authors are aware, this study is the first that reviews different integrative platforms and compares implemented NbS case studies in Europe, focusing on climate adaptation in coastal and estuarine areas. The study reviews previous NbS projects in Europe to enhance coastal ecosystems conservation and restoration for climate change mitigation and adaptation in coastal areas. The increase of NbS implementation in Europe is highlighted by our results; however its application is still highly biased towards northern countries, and a number of gaps are still hampering the replication of NbS such as general assumptions about NbS effectiveness and lack of site-specific data on physical and ecological processes; the minor participation of the private initiative in NbS funding; and the lack of quantitative effectiveness data in public sources.

Based on this analysis, we recommend that practitioners incorporate a detailed diagnosis of the site prior to NbS implementation in order to effectively evaluate site suitability, need, and community support for such a solution. A clear definition of objectives and expected co-benefits involving as many stakeholders as possible is also recommended. An integration and interconnection of different integrative platforms would be beneficial for the expansion of knowledge sharing networks.

AUTHOR CONTRIBUTIONS

RM, BR, and IM contributed to the conception and design of the study. RM wrote the first draft of the paper. IM wrote the introduction of the paper. IM and MR reviewed all the sections of the paper several times, actively contributing to the development of the final version. All authors contributed to manuscript revision, read, and approved the submitted version.

FUNDING

ACKNOWLEDGMENTS

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.829526/full#supplementary-material

REFERENCES

Anderson, C. C., and Renaud., F. G. (2021). A Review of Public Acceptance of Nature-Based Solutions: The 'why', 'when', and 'how' of Success for Disaster Risk Reduction Measures. *Ambio* 50 (8), 1552–1573. doi:10.1007/s13280-021-01502-4

Arkema, K. K., Griffin, R., Maldonado, S., Silver, J., Suckale, J., and Guerry, A. D. (2017). Linking Social, Ecological, and Physical Science to Advance Natural and Nature-Based Protection for Coastal Communities. *Ann. N.Y. Acad. Sci.* 1399 (1), 5–26. doi:10.1111/nyas.13322

Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., and Silliman, B. R. (2011). The Value of Estuarine and Coastal Ecosystem Services. *Ecol. Monogr.* 81 (2), 169–193. doi:10.1890/10-1510.1

Beck, M., and Airoldi, L. (2007). "Loss, Status and Trends for Coastal Marine Habitats of Europe," in *Oceanography and Marine Biology*. Editors R. Gibson,

R. Atkinson, and J. Gordon (Boca Raton, Florida: CRC Press), 345–405. 20074975:345–405. Oceanography and Marine Biology - An Annual Review. doi:10.1201/9781420050943.ch7

Brady, A. F., and Boda, C. S. (2017). How Do We Know if Managed Realignment for Coastal Habitat Compensation Is Successful? Insights from the Implementation of the EU Birds and Habitats Directive in England. *Ocean Coast. Manag.* 143 (July), 164–174. doi:10.1016/j.ocecoaman.2016.11.013

Bouma, T. J., Belzen, J. V., Balke, T., Zhu, Z., Airoldi, L., Blight, J., Davies, A. J., et al. (2014). Identifying Knowledge Gaps Hampering Application of Intertidal Habitats in Coastal Protection: Opportunities and Steps to Take. *Coastal Eng.* 87 (May), 147–157. doi:10.1016/j.coastaleng.2013.11.014

Chausson, A., Turner, B., Seddon, D., Chabaneix, N., Girardin, C. A. J., Kapos, V., et al. (2020). Mapping the Effectiveness of Nature-based Solutions for Climate Change Adaptation. *Glob. Change Biol.* 26 (11), 6134–6155. doi:10.1111/gcb.15310

Climate-ADAPT (2020a). A Transboundary Depoldered Area for Flood Protection and Nature: Hedwige and Prosper Polders — Climate-ADAPT. 2020. Available at: https://climate-adapt.eea.europa.eu/metadata/case-studies/a-transboundary-depoldered-area-for-flood-protection-and-nature-hedwige-and-prosper-polders.

Climate-ADAPT (2020b). About Climate-ADAPT — Climate-ADAPT. 2020. Available at: https://climate-adapt.eea.europa.eu/about.

Climate-ADAPT (2021a). Climate Adapt Search. 2021. Available at: https://climate-adapt.eea.europa.eu/#t-database.

Climate-ADAPT (2021b). Saltmarsh Recreation by Managed Realignment, Hesketh Out Marsh – UK — Climate-ADAPT. 2021. Available at: https://climate-adapt.eea.europa.eu/metadata/case-studies/saltmarsh-recreation-by-managed-realignment-hesketh-out-marsh-uk/#stake_holder_anchor.

E. Cohen-Shacham, G. Walters, C. Janzen, and S. Maginnis (Editors) (2016). Nature-Based Solutions to Address Global Societal Challenges (Gland, Switzerland: IUCN International Union for Conservation of Nature). doi:10.2305/IUCN.CH.2016.13.en

Creel, L. (2003). Ripple Effects: Population and Coastal Regions. 8.

Davies, C., Chen, W. Y., Sanesi, G., and Lafortezza, R., (2021). The European Union Roadmap for Implementing Nature-Based Solutions: A Review. Environ. Sci. Policy 121 (July), 49–67. doi:10.1016/j.envsci.2021.03.018

Debele, S. E., Kumar, P., Sahani, J., Marti-Cardona, B., Mickovski, S. B., Leo, L. S., et al. (2019). Nature-Based Solutions for Hydro-Meteorological Hazards: Revised Concepts, Classification Schemes and Databases. Environ. Res. 179 (December), 108799. doi:10.1016/j.envres.2019.108799

Doody, J. P. (2016). Category: Sand Dune Inventory of Europe (Doody Ed. 1991 & 2008). August 13, 2016. Available at: http://www.coastalwiki.org/wiki/Category:Sand_Dune_Inventory_of_Europe_(Doody_ed._1991_%26_2008.

Doody, J. P. (2013). Coastal Squeeze and Managed Realignment in Southeast England, Does it Tell Us Anything about the Future? Ocean Coast. Manag. 79, 34–41. doi:10.1016/j.ocecoaman.2012.05.008

Duarte, C. M., Losada, I. J., Hendriks, I. E., Mazarrasa, I., and Marbà, N. (2013). The Role of Coastal Plant Communities for Climate Change Mitigation and Adaptation. Nat. Clim. Change 3 (11), 961–968. doi:10.1038/nclimate1970

EC (2021a). A European Green Deal | European Commission. 2021. Available at: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en.

EC (2012). ICZM in Practice. Available at: https://ec.europa.eu/environment/iczm/practice.htm.

EC (2021b). Nature-Based Solutions | European Commission. European Commission - European Commission. 2021. Available at: https://ec.europa.eu/info/research-and-innovation/research-area/environment/nature-based-solutions_en.

EC (2021c). Recovery and Resilience Facility. European Commission - European Commission. Text2021. Available at: https://ec.europa.eu/info/business-economy-euro/recovery-coronavirus/recovery-and-resilience-facility_en.

EC (2013). The EU Strategy on Adaptation to Climate Change: Strengthening Europe's Resilience to the Impacts of Climate Change. Brussels: LU: Publications Office. Available at: https://data.europa.eu/doi/10.2834/5599.

EC (2015). Towards an EU Research and Innovation Policy Agenda for Nature-Based Solutions & Re-naturing Cities: Final Report of the Horizon 2020 Expert Group on 'Nature Based Solutions and Re Naturing Cities': (Full Version). LU: Publications Office. Available at: https://data.europa.eu/doi/10.2777/765301.

EcoShape (2020). "About EcoShape - EcoShape," in EcoShape - EN (Blog). Available at: https://www.ecoshape.org/en/about/.

Edwards, T. (2017). Current and Future Impacts of Sea Level Rise on the UK. London: Foresight, Government Office for Science. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/663885/Future_of_the_sea_-_sea_level_rise.pdf.

Environment Agency (2021). Saltmarsh Extent & Zonation. 2021. Available at: https://data.gov.uk/dataset/0e9982d3-1fef-47de-9af0-4b1398330d88/saltmarsh-extent-zonation.

Esteves, L. S. (2014). "Managed Realignment : A Viable Long-Term Coastal Management Strategy?," in SpringerBriefs in Environmental Science. 1st ed (Dordrecht: Springer). Netherlands : Imprint: Springer. doi:10.1007/978-94-017-9029-1

European Environment Agency (2019). Change in the Frequency of Flooding Events in Europe Given Projected Sea Level Rise under Two Climate Scenarios — European Environment Agency. Figure. December 4, 2019. Available at: https://www.eea.europa.eu/data-and-maps/figures/change-in-the-frequency-of.

European Environment Agency (2018). Climate-ADAPT Profile. 2018. Available at: https://climate-adapt.eea.europa.eu/about/climate-adapt-profile-final_2019.pdf.

Faivre, N., Fritz, M., Freitas, T., de Boissezon, B., and Vandewoestijne, S. (2017). Nature-Based Solutions in the EU: Innovating with Nature to Address Social, Economic and Environmental Challenges. Environ. Res. 159 (November), 509–518. doi:10.1016/j.envres.2017.08.032

Frantzeskaki, N. (2019). Seven Lessons for Planning Nature-Based Solutions in Cities. Environ. Sci. Policy 93 (March), 101–111. doi:10.1016/j.envsci.2018.12.033

Ganguli, P., and Merz, B. (2019). Extreme Coastal Water Levels Exacerbate Fluvial Flood Hazards in Northwestern Europe. Sci. Rep. 9 (1), 13165. doi:10.1038/s41598-019-49822-6

Garbutt, A. (2005). "Restoration of Intertidal Habitats by the Managed Realignment of Coastal Defences, UK," in Proceedings "Dunes and Estuaries 2005": International Conference on Nature Restoration Practices in European Coastal Habitats, Koksijde, Belgium, 19-23 September 2005 (VLIZ Special Publication). xiv + 685 pp. Belgium.19

Gedan, K. B., Kirwan, M. L., Wolanski, E., Barbier, E. B., and Silliman, B. R. (2011). The Present and Future Role of Coastal Wetland Vegetation in Protecting Shorelines: Answering Recent Challenges to the Paradigm. Clim. Change 106 (1), 7–29. doi:10.1007/s10584-010-0003-7

Giordano, R., Pluchinotta, I., Pagano, A., Scrieciu, A., and Nanu, F. (2020). Enhancing Nature-Based Solutions Acceptance through Stakeholders' Engagement in Co-benefits Identification and Trade-Offs Analysis. Sci. Total Environ. 713 (April), 136552. doi:10.1016/j.scitotenv.2020.136552

Global Center on Adaptation (2021). State and Trends in Adaptation Report 2020. Building Forward Better from Covid-19: Accelerating Action on Climate Adaptation. Rotterdam: Global Centre on Adaptation. Available at: https://www.cas2021.com/documents/reports/2021/01/22/state-and-trends-in-adaptation-report-2020.

Hanley, M. E., Hoggart, S. P. G., Simmonds, D. J., Bichot, A., Colangelo, M. A., Bozzeda, F., et al. (2014). Shifting Sands? Coastal Protection by Sand Banks, Beaches and Dunes. Coast. Eng. 87 (May), 136–146. doi:10.1016/j.coastaleng.2013.10.020

Heron, E. (2016). Case Study 62. Poole Bay Beach Replenishment Trial. Cranfield: The RRC. Available at: https://www.therrc.co.uk/sites/default/files/projects/62_poole.pdf.

ISO (2021). ISO - Developing Sustainably. 2021. Available at: https://www.iso.org/developing-sustainably.html.

Jongejan, R. B., and Maaskant, B. (2015). Quantifying Flood Risks in the Netherlands. Risk Anal. 35, 252–264. doi:10.1111/risa.12285

King, E., and Lester, J. N. (1995). The Value of Salt Marsh as a Sea Defence. Marine Pollut. Bull. 30 (3), 180–189. doi:10.1016/0025-326X(94)00173-7

Kirwan, M. L., and Megonigal, J. P. (2013). Tidal Wetland Stability in the Face of Human Impacts and Sea-Level Rise. Nature 504 (7478), 53–60. doi:10.1038/nature12856

Kopsieker, L., Gerritsen, E., Stainforth, T., Lucic, A., Costa Domingo, G., Naumann, S., et al. (2021). Nature-Based Solutions and Their Socio-Economic Benefits for Europe's Recovery: Enhancing the Uptake of Nature-Based Solutions across EU Policies. Brussels: European Environmental Policy (IEEP) and the Ecologic Institute. Available at: https://ieep.eu/uploads/articles/attachments/0b733817-b56a-4872-afc9-43ccff2ad6ba/Nature-based%20solutions%20and%20their%20socio-economic%20benefits%20for%20Europe%E2%80%99s%20recovery%20(IEEP%202021)%20WEB.pdf?v=63781383755.

Kulp, S. A., and Strauss., B. H. (2019). New Elevation Data Triple Estimates of Global Vulnerability to Sea-Level Rise and Coastal Flooding. Nat. Commun. 10 (1), 4844. doi:10.1038/s41467-019-12808-z

Kumar, P., Debele, S. E., Sahani, J., Aragão, L., Barisani, F., Basu, B., et al. (2020). Towards an Operationalisation of Nature-Based Solutions for Natural Hazards. Sci. Total Environ. 731, 138855. doi:10.1016/j.scitotenv.2020.138855

Kumar, P., Debele, S. E., Sahani, J., Rawat, N., Marti-Cardona, B., Alfieri, S. M., et al. (2021). An Overview of Monitoring Methods for Assessing the Performance of Nature-Based Solutions against Natural Hazards. Earth-Science Rev. 217, 103603. doi:10.1016/j.earscirev.2021.103603

Lee, H. S., Choi, Y.-J., and Woo, S.-B. (2021). Numerical Models in Coastal Hazards and Coastal Environment. Jmse 9 (5), 494. doi:10.3390/jmse9050494

Lin, N., Emanuel, K., Oppenheimer, M., and Vanmarcke, E. (2012). "Physically-Based Assessment of Hurricane Surge Threat under Climate Change," in Prof. Emanuel via Chris Sherratt. December. Available at: https://dspace.mit.edu/handle/1721.1/75773.

López-Dóriga, U., Jiménez, J. A., Bisaro, A., and Hinkel, J. (2020). Financing and Implementation of Adaptation Measures to Climate Change along the Spanish Coast. Sci. Total Environ. 712, 135685. doi:10.1016/j.scitotenv.2019.135685

Madsen, H. M., Mikkelsen, P. S., and Blok, A. (2019). Framing Professional Climate Risk Knowledge: Extreme Weather Events as Drivers of Adaptation Innovation in Copenhagen, Denmark. *Environ. Sci. Policy* 98, 30–38. doi:10.1016/j.envsci.2019.04.004

Martínez, M. L., Intralawan, A., Vázquez, G., Pérez-Maqueo, O., Sutton, P., and Landgrave, R. (2007). The Coasts of Our World: Ecological, Economic and Social Importance. *Ecol. Econ.* 63 (2–3), 254–272. doi:10.1016/j.ecolecon.2006.10.022

Masselink, G., and Russell, P. (2013). Impacts of Climate Change on Coastal Erosion. Pdf. *MCCIP Sci. Rev.* 2013 16, doi:10.14465/2013.ARC09.071-086

Masselink, G., Scott, T., Poate, T., Russell, P., Davidson, M., and Conley, D. (2016). The Extreme 2013/2014 Winter Storms: Hydrodynamic Forcing and Coastal Response along the Southwest Coast of England. *Earth Surf. Process. Landforms* 41 (3), 378–391. doi:10.1002/esp.3836

Maul, G. A., and Duedall, I. W. (2019). "Demography of Coastal Populations," in *Encyclopedia of Coastal Science*Charles W. Finkl and Christopher Makowski, 692–700 (Cham: Springer International Publishing), 692–700. doi:10.1007/978-3-319-93806-6_115

Mcleod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., et al. (2011). A Blueprint for Blue Carbon: Toward an Improved Understanding of the Role of Vegetated Coastal Habitats in Sequestering CO_2. *Front. Ecol. Environ.* 9 (10), 552–560. doi:10.1890/110004

Menéndez, P., Losada, I. J., Torres-Ortega, S., Narayan, S., and Beck, M. W. (2020). The Global Flood Protection Benefits of Mangroves. *Sci. Rep.* 10 (1), 4404. doi:10.1038/s41598-020-61136-6

Morris, R. L., Konlechner, T. M., Ghisalberti, M., and Swearer, S. E. (2018). From Grey to Green: Efficacy of Eco-Engineering Solutions for Nature-Based Coastal Defence. *Glob. Change Biol.* 24 (5), 1827–1842. doi:10.1111/gcb.14063

Narayan, S., Beck, M. W., Reguero, B. G., Losada, I. J., van Wesenbeeck, B., Pontee, N., et al. (2016). The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences. *PLOS ONE* 11 (5), e0154735. doi:10.1371/journal.pone.0154735

NATURVATION (2017a). About | NATURVATION. 2017. Available at: https://naturvation.eu/about.

NATURVATION (2017b). Urban Nature Atlas. Text. NATURVATION. 2017. Available at: https://naturvation.eu/atlas.

Nellemann, C., Corcoran, E., Duarte, C. M., Valdes, L., DeYoung, C., Fonseca, L., et al. (2009). *Blue Carbon: The Role of Healthy Oceans in Binding Carbon: A Rapid Response Assessment.* Arendal, [Norway]: GRID-Arendal.

Ondiviela, B., Losada, I. J., Lara, J. L., Maza, M., Galván, C., Bouma, T. J., et al. (2014). The Role of Seagrasses in Coastal Protection in a Changing Climate. *Coast. Eng.* 87, 158–168. doi:10.1016/j.coastaleng.2013.11.005

Oppenheimer, M., Glavovic, B. C., Hinkel, J., van de Wal, R., Magnan, A. K., Abd-Elgawad, A., et al. (2019). Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. Available at: https://www.ipcc.ch/srocc/chapter/chapter-4-sea-level-rise-and-implications-for-low-lying-islands-coasts-and-communities/.

OPPLA (2021). About | Oppla. 2021. Available at: https://oppla.eu/about.

Persson, J. (2013). Perceptions of Environmental Compensation in Different Scientific Fields. *Int. J. Environ. Stud.* 70 (4), 611–628. doi:10.1080/00207233.2013.835526

Pontee, N., Narayan, S., Beck, M. W., and Hosking, A. H. (2016). Nature-Based Solutions: Lessons from Around the World. *Proc. Institution Civ. Eng. - Marit. Eng.* 169 (1), 29–36. doi:10.1680/jmaen.15.00027

Potouroglou, M., Bull, J. C., Krauss, K. W., Kennedy, H. A., Fusi, M., Daffonchio, D., et al. (2017). Measuring the Role of Seagrasses in Regulating Sediment Surface Elevation. *Sci. Rep.* 7 (1), 11917. doi:10.1038/s41598-017-12354-y

Reguero, B. G., Losada, I. J., Díaz-Simal, P., Méndez, F. J., and Beck, M. J. (2015). Effects of Climate Change on Exposure to Coastal Flooding in Latin America and the Caribbean. *PLOS ONE* 10 (7), e0133409. doi:10.1371/journal.pone.0133409

RESTORE (2014). RESTORE - Rivers Engaging, Supporting and Transferring KnOwledge for Restoration in Europe. Final Report. Available at: https://restorerivers.eu/wiki/index.php?title=Main_Page.

Rodriguez, A. B., Fodrie, F. J., Ridge, J. T., Lindquist, N. L., Theuerkauf, E. J., Coleman, S. E., et al. (2014). Oyster Reefs Can Outpace Sea-Level Rise. *Nat. Clim. Change* 4 (6), 493–497. doi:10.1038/nclimate2216

Ruangpan, L., Vojinovic, Z., Di Sabatino, S., Leo, L. S., Capobianco, V., Oen, A. M. P., et al. (2020). Nature-Based Solutions for Hydro-Meteorological Risk Reduction: A State-Of-The-Art Review of the Research Area. *Nat. Hazards Earth Syst. Sci.* 20 (1), 243–270. doi:10.5194/nhess-20-243-2020

Serrano, O., Lovelock, C. E., B. Atwood, T., Macreadie, P. I., Canto, R., Phinn, S., et al. (2019). Australian Vegetated Coastal Ecosystems as Global Hotspots for Climate Change Mitigation. *Nat. Commun.* 10 (1), 4313. doi:10.1038/s41467-019-12176-8

Seddon, N., Chausson, A., Berry, P., Girardin, C. A. J., Smith, A., and Turner, B. (2020). Understanding the Value and Limits of Nature-Based Solutions to Climate Change and Other Global Challenges. *Philos. Trans. R. Soc. B* 375 (1794), 20190120. doi:10.1098/rstb.2019.0120

Statistical Office of the European Communities (2011). Eurostat Regional Yearbook 2011.

Syvitski, J. P. M., Kettner, A. J., Overeem, I., Hutton, E. W. H., Hannon, M. T., Brakenridge, G. R., et al. (2009). Sinking Deltas Due to Human Activities. *Nat. Geosci.* 2 (10), 681–686. doi:10.1038/ngeo629

Temmerman, S., Meire, P., Bouma, T. J., Herman, P. M. J., Ysebaert, T., and De Vriend, H. J. (2013). Ecosystem-Based Coastal Defence in the Face of Global Change. *Nature* 504 (7478), 79–83. doi:10.1038/nature12859

the RRC (2014a). About Us. 2014. Available at: https://www.therrc.co.uk/rrc.

the RRC (2014b). EU RiverWiki | the RRC. 2014. Available at: https://www.therrc.co.uk/eu-riverwiki.

the RRC (2014c). UK Projects Map | the RRC. 2014. Available at: https://www.therrc.co.uk/uk-projects-map.

Toxopeus, H., and Polzin, F. (2021). Reviewing Financing Barriers and Strategies for Urban Nature-Based Solutions. *J. Environ. Manag.* 289, 112371. doi:10.1016/j.jenvman.2021.112371

Van Coppenolle, R., and Temmerman, S. (2020). Identifying Ecosystem Surface Areas Available for Nature-Based Flood Risk Mitigation in Coastal Cities Around the World. *Estuaries Coasts* 43 (6), 1335–1344. doi:10.1007/s12237-020-00718-z

van de Hurk, B., Tank, A. K., Lenderink, G., Ulden, A. V., Oldenborgh, G. J. V., Katsman, J., et al. (2006). *KNMI Climate Change Scenarios 2006 for the Netherlands.* WR 2006-01.

van Wesenbeeck, B. V., de Boer, W., Narayan, S., van der Star, W. R. L., and de Vries, M. B. (2017). Coastal and Riverine Ecosystems as Adaptive Flood Defenses under a Changing Climate. *Mitig. Adapt Strateg. Glob. Change* 22 (7), 1087–1094. doi:10.1007/s11027-016-9714-z

Vo, Q. T., Kuenzer, C., Vo, Q. M., Moder, F., and Oppelt, N. (2012). Review of Valuation Methods for Mangrove Ecosystem Services. *Ecol. Indic.* 23, 431–446. doi:10.1016/j.ecolind.2012.04.022

Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Bianchi, A., Dottori, F., and Feyen, L. (2018). Climatic and Socioeconomic Controls of Future Coastal Flood Risk in Europe. *Nat. Clim. Change* 8 (9), 776–780. doi:10.1038/s41558-018-0260-4

Zhu, Z., Vuik, V., Visser, P. J., Soens, T., Wesenbeeck, B. V., Koppel, J. V., et al. (2020). Historic Storms and the Hidden Value of Coastal Wetlands for Nature-Based Flood Defence. *Nat Sustain.* 3 (10), 853–862. doi:10.1038/s41893-020-0556-z