Ecological Indicators 183 (2026) 114629

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Nature-based adaptation in human dominated coastal ecosystems☆

Fabienne Horneman[a,b,1], Alice Stocco[b,1], Paolo Comandini[c], Alberto Barausse[c], Nuno Caiola[d], Agustín Sánchez-Arcilla[e], Vicente Gracia[f], Richard Marijnissen[g], Sara Pino Cobacho[g], Luciana Villa Castrillón[h,i], Joanna Staneva[h], Elitsa Hineva[j], Nataliya Andreeva[j], Massimiliano Marino[k], Rosaria Ester Musumeci[k], Julien Dalle[l], Mathis Cognat[l], Olivier Boutron[m], Morgane Jolivet[m], Avi Uzan[n], Shiri Zemah-Shamir[o], Gregorz Rozynski[p], Elisa Furlan[a,b], Ignacio Gatti[a,b], Caterina Dabalà[q], Fabio Pranovi[b], Andrea Critto[b,a], Silvia Rova[b,r], Silvia Torresan[a,b,*]

[a] CMCC Foundation - Euro-Mediterranean Center on Climate Change, Italy
[b] Department of Environmental Sciences, Informatics and Statistics, University Ca' Foscari Venice, Via Torino 155, 30172 Venezia, Italy
[c] Department of Biology, University of Padova, via U. Bassi 58/B, 35131 Padova, Italy
[d] Eurecat, Technology Center of Catalonia, Dept. Climate Solutions and Ecosystem Services, Spain
[e] Universitat Politècnica de Catalunya (UPC), Spain
[f] Laboratori d'Enginyeria Marítima, Universitat Politècnica de Catalunya, Jordi Girona, 1 - 3, Mòdul D1, Barcelona 08034, Spain
[g] Deltares, Boussinesqweg 1, Delft 2629HV, the Netherlands
[h] Institute of Coastal Systems - Analysis and Modeling, Helmholtz-Zentrum Hereon, Geesthacht, Germany
[i] Institute for Chemistry and Biology of the Marine Environment, University of Oldenburg, Wilhelmshaven, Germany
[j] Institute of Oceanology, Bulgarian Academy of Sciences, 40 Parvi may Blvd., 9000 Varna, Bulgaria
[k] Department of Civil Engineering and Architecture, University of Catania, Via Santa Sofia 64, 95123 Catania, Italy
[l] Seaboost, 34000 Montpellier, France
[m] Tour du Valat Research Institute, 13200 Arles, France
[n] Israel Nature and Park Authority (INPA), Israel
[o] School of Sustainability, Reichman University, 8 Ha'Universita st.Herzliya, Herzliya 4610101, Israel
[p] Institute of Hydro-Engineering, Polish Academy of Sciences, 7 Kościerska, 80-328 Gdańsk, Poland
[q] Consortium for Coordination of Research Activities Concerning the Venice Lagoon System (CORILA), San Polo 19, 30125 Venezia, Italy
[r] International Centre for Climate Change Research and Studies, San Marco 2847, 30124 Venice, Italy

ARTICLE INFO

Keywords:
Coastal restoration
Nature-based techniques
Coastal ecosystems
River-to-sea continuums
Expert-based
Climate acceleration
Adaptive management

ABSTRACT

Ecosystems along river-to-sea continuums face urgent challenges that demand swift restoration interventions, often exceeding the data availability, collection and testing capacity. This makes expert- and consensus-based approaches vital for guiding decisions, particularly in data-scarce coastal regions. With the aim to provide practical guidance for assessing the applicability of different restoration techniques, this study involved a group of 23 experts from various European and Mediterranean regions to evaluate 49 restoration techniques tested recently in nine sites, representing diverse coastal ecosystems. Through a Delphi-based expert elicitation, a series of gray, hybrid, and green restoration techniques was assessed in terms of their structural and functional performance. Additionally, the assessment of the pressures affecting the regions allowed exploring the restoration techniques' resilience to both natural and anthropogenic pressures and impacts. Results from the data collected so far suggest that, while green restoration techniques are environmentally friendly and significantly support natural processes, their limited scale of influence makes them vulnerable when pressures are strong or widespread on the ecosystem. This often leads to opting for hybrid or engineering-based solutions for restoration, as they provide a more robust structure and longevity albeit with reduced capacity to foster natural processes. This result underscores a critical dilemma: while green and/or integrated solutions can help mitigate human-induced impacts and digital tools may support decision-making, restoration efforts alone may sometimes be insufficient if

☆ This article is part of a Special issue entitled: 'NbS for Holistic Management' published in Ecological Indicators.

* Corresponding author at: CMCC Foundation - Euro-Mediterranean Center on Climate Change, Italy.
E-mail address: silvia.torresan@cmcc.it (S. Torresan).

[1] These authors contributed equally to the delivery of this manuscript.

https://doi.org/10.1016/j.ecolind.2026.114629
Received 7 April 2025; Received in revised form 25 November 2025; Accepted 12 January 2026
Available online 28 January 2026
1470-160X/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

the underlying anthropogenic pressures on human-dominated coastal ecosystems remain unaddressed. Subsequently, the identified techniques and their performance evaluated under current and future conditions have been compiled into an open-source, interactive digital tool, designed to assist decision-makers and practitioners in selecting the most suitable restoration strategies by leveraging the knowledge acquired through ongoing experiences in coastal restoration. This digital platform not only facilitates access to information but also enables the integration of new data on emerging techniques, making it a dynamic and evolving resource for coastal restoration management.

1. Introduction

With the potential to play a crucial role in guiding ecological restoration, Nature-Based Solutions (NBSs) are prominent terms, both in the research and political field (Pittman et al., 2022; Cohen-Shacham et al., 2016; Xu et al., 2023). The European Union (EU), in particular the European Commission, has been promoting the adoption of solutions inspired by nature as part of the restoring and rebalancing of the relationship between nature and society (Davies et al., 2021; Moraes et al., 2022). Positioning itself as a leader in "innovating with nature", the EU has been working on making NBSs more accessible through knowledge acquisition and the expansion of the evidence base regarding restoration performance (Faivre et al., 2017). To support this task and assess the outcome of using NBSs for adaptive management, the coordination of restoration case-studies, and the collection of data and outcomes about different techniques into open-science databases, is highly recommended (Dunlop et al., 2023). However, this task is often difficult to achieve since the research field, and subsequent evidence collected through monitoring is still emerging. Additionally, reflecting their need for flexibility in addressing various environmental and societal challenges, the broad set of NBSs can include a combination of green, hybrid, and nature-inspired gray solutions (Cohen-Shacham et al., 2016; Hudson et al., 2021). In ecological restoration, green solutions are considered nature-based approaches that rely on natural elements and ecological processes; hybrid solutions are those which combine natural elements with engineering structures, like integrating artificial barriers with vegetation for increased ecological resilience; gray solutions are primarily engineering-based, such as concrete dams or seawalls, which provide structural change into the ecosystem with the aim to drive some desirable processes rather than others. To widely implement relevant restoration actions that remediate or mitigate the negative effects occurring to an ecosystem (Hudson et al., 2021), whether based on NBS and green solutions, or more on engineering-driven gray structures, there is a need to learn from the experiences with established approaches (O'Leary et al., 2023). While coastal restoration is essential to meet ecosystem conservation and sustainability objectives (Shumway et al., 2021), and restoration of the river-to-sea continuum plays a paramount role in the current focus on NBSs to address societal challenges (Bayraktarov et al., 2020), compared to terrestrial interventions, coastal restoration is often less studied since they are mostly executed at a smaller scale (Osinga et al., 2024; Saunders et al., 2024) or as isolated projects, often implemented as pilots. This fragmented, small-scale implementation hampers the upscaling of restoration as a climate adaptation strategy.

Governments have put much effort into coastal and transitional restoration; however, most interventions lack systematic studies on pressures and processes that may affect the restoration performance (Zhao et al., 2016), or lack monitoring of restoration success over the long-term temporal scales. This is of particular importance considering that without restoration suited to high or increasing pressures, such as climate change, sea level rise, coastal development, and eutrophication, it will be difficult to meet EU and international policy targets (Sánchez-Arcilla et al., 2022). Hence, the identification of effective techniques while considering contemporary and future pressures is a pressing issue (Morris et al., 2018), and guidelines underpinning evidence-based upscaling of marine coastal ecosystem restoration, including functional and structural design guidance, are needed (Saunders et al., 2024; Montanari, 2017).

Accordingly, there is a need to explore the design, technical implementation and success of different restoration techniques, as well as the influence of natural and anthropogenic pressures and their impacts on the processes influenced by restoration (Bianciardi et al., 2023; Jordan and Fröhle, 2022). Additionally, gathering information and data about the overall structural characteristics that give durability to a restoration technique with its intrinsic point of strength and vulnerabilities, along with the estimates of the time needed for a technique to be put in place and start working within the ecosystem, is of the utmost importance when planning a restoration intervention. This should be explored alongside the restoration technique potential for mitigating pressures and preventing negative impacts on the ecosystem, which is preeminent for decision-makers, who often have a clear understanding of the environmental issues afflicting their territory, but may not be fully equipped to identify from the onset the key natural processes they need to leverage to alleviate environmental problems in complex socio-ecological settings. Moreover, the understanding of the coastal ecosystem functioning from empirical data is often incomplete, context- and scale-dependent, and there is an urgent need to bridge the gap between limited empirical information and effective decision-making for restoration (Gladstone-Gallagher et al., 2019). When a technique or methodology is applied to an ecosystem, especially in the early phases of testing and experimentation, data scarcity and varying contexts are common barriers in ecological research (Sánchez-Arcilla et al., 2022; Zhao et al., 2016). This challenge is particularly pronounced when the testing phase involves not only the application of a well-known technique in a new context but also the use of emerging methodologies that are being tested for the first time, as is often the case with NBSs and restoration approaches on highly impacted coastal areas. Hence, learning by comparison is one of the main strategies recommended for the uptake and implementation of restoration techniques (Sarabi et al., 2022; Walters and Holling, 1990), and expert- and consensus-based approaches have been widely used since they represent a valuable method to inform future decisions and research directions (Waring, 2024; Seijger et al., 2014; Khodyakov et al., 2023).

Due to their local ecological knowledge, scientific and practitioners community plays a central role in making adaptation knowledge more accessible for coastal planners and policymakers (Weible et al., 2010; Hayes et al., 2018), and expert elicitation addresses the urgency-uncertainty predicament by securing best available data (Jacobs et al., 2015). In fact, expert-based opinions in ecology have shown to be extremely valuable, especially in contexts where empirical data is incomplete, insufficient, or too difficult to obtain due to the complexity of the context (Campagne and Roche, 2018). Moreover, this approach provides several advantages that counterbalance the possible uncertainty related to the expression of the subjective opinion of experts: on the one hand, a group of local experts has the ability to quickly synthesize information from multiple disciplines (e.g., hydrology, botany, ecology) and across different scales by also leveraging their knowledge of specific ecosystems, species, or regions (Brook and McLachlan, 2005). This tailored approach is often faster and less expensive than conducting new field studies, experiments, or large-scale surveys, making it particularly useful for preliminary assessments. On the other hand, experts can offer qualitative or semi-quantitative insights for scenarios that are complex or too time-consuming to simulate with existing models, especially under conditions of uncertainty. This is possible because experienced scientists develop an intuitive understanding of ecological processes and patterns over years of study, allowing them to anticipate outcomes that models or less experienced individuals might overlook (Zayonc and Coomes, 2022). As such, expert input can play a crucial role in adaptive management strategies, where iterative decisions are based on the best available information. Additionally, experts excel at translating complex ecological knowledge into actionable and practical recommendations for policymakers and stakeholders (Burkhard and Maes, 2017).

Building upon these considerations, this study aimed to establish a collection of restoration practices in the river-delta-coast continuum, including recent case studies from various coastal landscapes in the EU (the Atlantic Ocean, the Baltic Sea, the Black Sea, the Mediterranean Sea, and the North Sea) as a guideline for practitioners and decision-makers. In particular, through the consideration of these different land-seascape lenses a systematic, tool-supported approach linked expert knowledge with practical restoration implementation by addressing the following questions: i) Which restoration techniques are recommended by experts to mitigate the effects of pressures and impacts on coastal ecosystems?; ii) What restoration techniques have been observed, and how does the chosen technique influence natural processes and ecosystem functions?; and iii) How could the structural stability and performance of restoration techniques be impacted by varying intensities of natural and anthropogenic pressures? To capitalize on the experience and the knowledge obtained in the context of recent restoration interventions, the information collected from case studies participating in the project have been formalized into an open source digital tool. It is designed to support decision making process and knowledge sharing for restoration planning. Moreover, it allows for cross-site comparison and may be extended with additional information in the future. Thus, this work presents the expert-based characterization of pressures and the scoring of the restoration techniques that are suggested to mitigate them. Considering the practical implications of the findings, the results highlight the potential of digital tools and shared knowledge to guide decision-makers in selecting and implementing effective restoration strategies in coastal ecosystems.

2. Methodology

2.1. Short description of the case studies

Regional marine system differences across the Mediterranean, Baltic, and Atlantic basins influence restoration applicability. The Mediterranean is microtidal, generally oligotrophic (Woodroffe and Murray-Wallace, 2012); the Baltic is brackish, low-salinity, and eutrophication-prone with limited water exchange (Elmgren, 2001; Meier et al., 2018; Carstensen et al., 2014); while the Atlantic is macrotidal, wave-dominated, and sediment-rich (Schmitt and Chaumillon, 2023; Ostojic et al., 2025). The Black Sea is a semi-enclosed basin with restricted exchange through the Bosporus, strong halocline stratification, and widespread deep-water anoxia (Murray et al., 1989; Stanev et al., 2019), conditions that influence sediment retention, benthic sensitivity, and biogeochemical cycling. In contrast, the North Sea is a shallow, high-energy shelf system characterized by strong tidal currents, intensive wave action, and high sediment mobility (Baeye et al., 2011; Huthnance et al., 2016), resulting in dynamic seabed habitats and rapid ecological responses. These contrasting hydrodynamic and biogeochemical regimes shape sediment transport, habitats, and biological responses, requiring region-specific application of restoration techniques.

The case studies included in this work have been derived from the Horizon 2020 REST-COAST[2] EU research project (https://rest-coast.eu/), running from 2021 to 2026, which considers different pilot sites located in the main European marine coastal regions (Fig. 1). These case studies range from 32 to 300,000 ha and encompass a diverse array of environments, reflecting the broad scope of ecosystems present along Europe's coasts. The pilots indeed span from a heterogeneous coastal area represented by the Wadden Sea; coastal lagoons, such as in the pilot sites of Arcachon Bay, Venice lagoon, Sicily lagoons; coastal bays like Foros Bay; coastal wetland as those represented by the Vistula lagoon; estuarine and delta ecosystems like the Ebro Delta, the Rhône Delta; and finally a wetland connected to the sea in Nahal Dalia. These pilots include several marine and coastal habitats such as intertidal mudflats and saltmarshes (especially in Venice, Sicily and Wadden Sea), dynamic estuarine systems and deltas with sandy beaches and coastal dunes (like the Ebro and the Rhone Delta), as well as sheltered bays (as it is the case of Foros Bay, Arcachon Bay, and Vistula Lagoon). Most of the pilots host marine and brackish habitats supporting seagrass meadows (See Table 1).

While the restoration interventions targeted also the provisioning of a selection of ecosystem services, spanning from Blue Carbon sequestration, water purification, and reduction of flooding risk, with the approaches highlighted in this work, these case studies especially aim to reduce coastal erosion risks and provide gains in biodiversity. The heterogeneity of the sites allows for illustrating a variety of coastal ecosystems, their challenges and restoration solutions, and therefore provides a holistic understanding of restoration types and scales in the European river-coast-sea continuum that have been implemented to tackle climate-related and biodiversity loss challenges, as well as of the most relevant pressures and impacts that affect coastal areas and their habitat.

2.2. Assessment methods

Expert opinion can be useful for identifying and developing consensus on complex issues for which there is a limited or conflicting knowledge base (Gobster et al., 2020). Among the various methods for structuring expert input, the Delphi technique is well established and has received increased use in the environmental management field (Gobster et al., 2020). Emerging in the 1950s, the Delphi technique has increasingly been adopted in environmental sciences and is particularly useful for issues that are largely unexplored, difficult to define, highly context and expertise-specific, or future-oriented (Toumbourou et al., 2024). The technique aims to solicit the advice of experts and, where possible, forge a consensus (Orsi et al., 2011; Khodyakov et al., 2023). The iterative process to obtain expert consensus is considered to be more reliable as it maximizes the benefit of engaging a group of knowledgeable individuals while minimizing individual biases (Khodyakov et al., 2023; Brady, 2015).

The Delphi approach was selected because it enables the systematic elicitation of expert knowledge across geographically distributed sites and disciplines, reducing the influence of dominant voices through anonymity and iterative feedback. Compared with more recent participatory techniques (e.g., focus groups, co-design workshops, or multi-criteria decision analysis), the Delphi method is particularly suitable for contexts where empirical data are scarce and expert knowledge constitutes the primary source of evidence for cross-site evaluation (Campagne and Roche, 2018; Gobster et al., 2020).

In this study, structured communication was established between the site experts participating to adopt a modified Delphi approach, implemented in a structured single-round format, tailored to the multi-site design of the project. Instead of multiple iterative rounds, experts

[2] REST-COAST (Large-scale RESToration of COASTal ecosystems through river to sea connectivity)

EU Marine coastal region	Name of the case study	Type of ecosystem
The North Sea	Wadden Sea (The Netherlands & Germany)	Coastal sea, estuary, wetlands
The Baltic Sea	Vistula Lagoon (Poland)	Coastal lagoon
The Atlantic Ocean	Arcachon Bay (France)	Marine bay, coastal lagoon
The Black Sea	Foros Bay (Bulgaria)	Marine (coastal) bay
The Mediterranean Sea	Ebro Delta (Spain)	River delta, wetlands, beaches, dunes
	Rhône Delta (France)	River delta, coastal lagoon
	Venice Lagoon (Italy)	Coastal lagoon
	Sicily Lagoon (Italy)	Coastal lagoon(s)
	Nahal Dalia (Israel)	Wetland, estuary

Fig. 1. REST-COAST case studies in relation to EU marine coastal regions, ecosystem types, and type of restoration interventions implemented in the pilot site.

provided quantitative evaluations through a standardized scoring matrix covering all restoration techniques. This adaptation allowed for the integration of knowledge from nine geographically distributed panels while maintaining the key Delphi principles of structured expert elicitation, anonymity of individual responses, and reduction of dominant bias. Similar structured adaptations of the classical Delphi have been applied in environmental and restoration contexts where distributed expertise or limited time frames precluded iterative rounds (Mukherjee et al., 2018; Khodyakov et al., 2023).

The elicitation was conducted in three phases between May and December 2024 (Fig. 2), allowing the iterative refinement of the methodology (further detailed in sections 2.2.1, 2.2.2, and 2.2.3), as well as the consistent contribution of pilot site experts.

2.2.1. Site experts & baseline information

The **first phase** of the adapted Delphi method implemented in this study included the identification of site experts, as well as the development and distribution of a questionnaire addressed to them (Fig. 2, Phase I). The expert participants were identified by the research team according to their engagement in restoration efforts in the case studies, resulting in the inclusion of 23 individuals, two to four experts per site, with various backgrounds including ecology (all 23), eco-hydrology and modeling (13), ornithology (2), ichthyology (3), environmental and restoration engineering (8), and other relevant fields in the sector of the Environmental Sciences. Experts were invited to participate in an online meeting in May 2024 during which they were introduced to the research topic. Subsequently, in June 2024, an online questionnaire (SM I) was circulated among the pilot site experts. This questionnaire included clarifying descriptions of the terminology applied in this work, and dove deeper into two overarching topics to collect baseline information about: i) the techniques and materials used to construct restoration interventions; and ii) the pressures threatening the restoration sites. While experts were selected among REST-COAST partners due to their direct engagement in restoration design and implementation, the large heterogeneity across disciplines and regions helps reduce internal confirmation bias, and the open-source platform allows future integration of external expert assessments.

2.2.2. Characterising pressures and scoring restoration techniques: consensus-based pilot insights

In the **second phase** of the Delphi approach, data from the baseline questionnaire and existing pilot information were consolidated into site-specific sheets for expert evaluations (SM II - Site sheet template), which were filled by the site experts and complemented through pilot workshops. In this phase of the study (Fig. 2, Phase II), the site experts scored the potential contribution of restoration techniques to relevant natural

Table 1
REST-COAST case studies details, with pressures to which the ecosystems are exposed.

Name of the case study	Type of ecosystem	Natural impacts-pressures triggered by anthropogenic stressors-triggers	Anthropogenic impacts-pressures
Wadden Sea (The Netherlands & Germany)	Coastal sea, estuary, wetlands	Drought, Local warming due to CC, Relative sea level rise, Sediment availability, Salinisation, Storm intensification, Turbidity	Invasive species, Land reclamation, Nautical traffic and waves, Dredging
Vistula Lagoon (Poland)	Coastal lagoon	Drought, Local warming due to CC, Relative sea level rise, Storm intensification	Eutrophication / Nutrient input, Storm surges, Land use change
Arcachon Bay (France)	Marine bay, coastal lagoon	Drought, Erosion, Flow velocity, Turbidity, Invasive species, Local warming due to CC, Relative sea level rise, Storm intensification, Thermal stress	Boat anchoring, Coastal artificialisation, Dredging, Nautical traffic and waves, Oyster farming
Foros Bay (Bulgaria)	Marine (coastal) bay	Drought, Local warming due to CC, Relative sea level rise, Storm intensification	Nutrient input, Natural flow, modification, Coastal artificialisation, Turbidity, Pollution / nutrients
Ebro Delta (Spain)	River delta, wetlands, beaches, dunes	Drought, Erosion, Land subsidence, Local warming due to CC, Relative sea level rise, Flooding, Storm intensification	Agricultural intensification, Decreasing river flow, Invasive species, Pollution, Sediment availability
Rhône Delta (France)	River delta, coastal lagoon	Drought, Erosion, Local warming due to CC, Nutrient input, Relative sea level rise, Sediment availability, Storm intensification, Thermal stress, Invasive species	Natural flow modification
Venice Lagoon (Italy)	Coastal lagoon	Drought, Local warming due to CC, Relative sea level rise, Sediment deficit, Storm intensification	Dredging, Pollution, Nautical traffic and waves, Nutrient input
Sicily Lagoon (Italy)	Coastal lagoon(s)	Drought, Storm intensification, Relative sea level rise	Hunting, Pollution, Agricultural, intensification, Population, Natural flow modification, Coastal artificialisation
Nahal Dalia (Israel)	Wetland, estuary	Drought	Natural flow modification, Water abstraction, Pollution, Natural flow modification

processes on a scale from 1 to 5, where 1 represents "no enhancement" and 5 represents "significant enhancement". If the techniques were deemed irrelevant for enhancing a specific process, or if the uncertainty was too high, the score was left blank. The selected processes included sedimentation, reduction of current velocity, wave height reduction, nutrient retention and removal, carbon sequestration, plant community stabilization, and habitat maintenance for fish and birds. Based on these evaluations, the processes were categorized into three groups: "biogeochemical cycle supporting techniques" (e.g., nutrient and carbon), "life cycle supporting techniques" (e.g., plant and animal life cycles), and "morphological supporting techniques" (e.g., sedimentation, bottom velocity). Cumulative scores for each process category were calculated for each site, reflecting the expert assessments of each technique's impact. In the following step, experts evaluated the structural characteristics of the restoration techniques they implemented in their own site, by evaluating the time needed for construction, achieving structural stability, and delivering the intended ecological processes. They also assessed the longevity of the techniques compared to a 10-year span, the use of locally sourced materials, and their biodegradability. These assessments were based on qualitative scales, with lower scores indicating lower sustainability or longer times to reach structural and functional stability, and higher scores indicating better sustainability or shorter times.

Finally, the experts were asked to evaluate the long-term performance of restoration techniques under different pressure scenarios (low, medium, and high intensity), where pressure intensity levels were defined as expert-derived relative gradients adapted to each coastal system, consistent with Delphi methodology for heterogeneous contexts where comparable physical thresholds are not available or do not make sense. This evaluation aimed to understand the potential flexibility for transition into a new planning approach based on the necessity required for a pressure in a specific area (Lawrence et al., 2018) in light of the potential exacerbation of pressures due to both climate change and human activities (Borja et al., 2024). The scores represent the impact of these pressures on interventions carried out using these restoration techniques, ranging from "no impact" to "complete destruction". This expert-driven process provides valuable insights into the potential performance of restoration techniques and helps prioritize them based on different pressure scenarios. Pressures were classified as anthropogenic or natural following the Imp-Press conceptual framework (Segurado et al., 2018), where human-derived pressures (e.g., boat traffic, land reclamation, nutrient loading) are distinguished from natural or climatic ones (e.g., sea-level rise, storms). As is common in consensus-based expert assessments, not all experts rated all technique vs. process combinations, since certain processes may not be relevant for specific interventions or sites. Cumulative scores for each technique and process category were therefore calculated as the mean of all available expert scores, treating blank cells as "not applicable", consistent with Delphi practices. This approach ensures that processes not relevant to a given technique do not bias the results, and maintains comparability across sites despite differences in ecological context and technique applicability, with an approach which is consistent with established practice in expert consensus studies (Campagne and Roche, 2018).

2.2.3. *Building restoration techniques expert consensus*

Following the completion of all site sheets, in the **third phase**, all information was processed and combined into a database of restoration techniques (Fig. 2, Phase III). The use of an assemblage of interventions has been recommended as a tool for managing ecosystems and their related natural processes since these 'portfolios' provide decision-makers with a variety of options to evaluate and choose the most appropriate restoration technique for their site (Alvarez et al., 2017). To obtain this collection of restoration techniques, the results from the nine site sheets were combined and organized in a matrix that links the impact of pressures on the techniques. The resulting dataset was prepared for running statistical tests to determine if there were significant

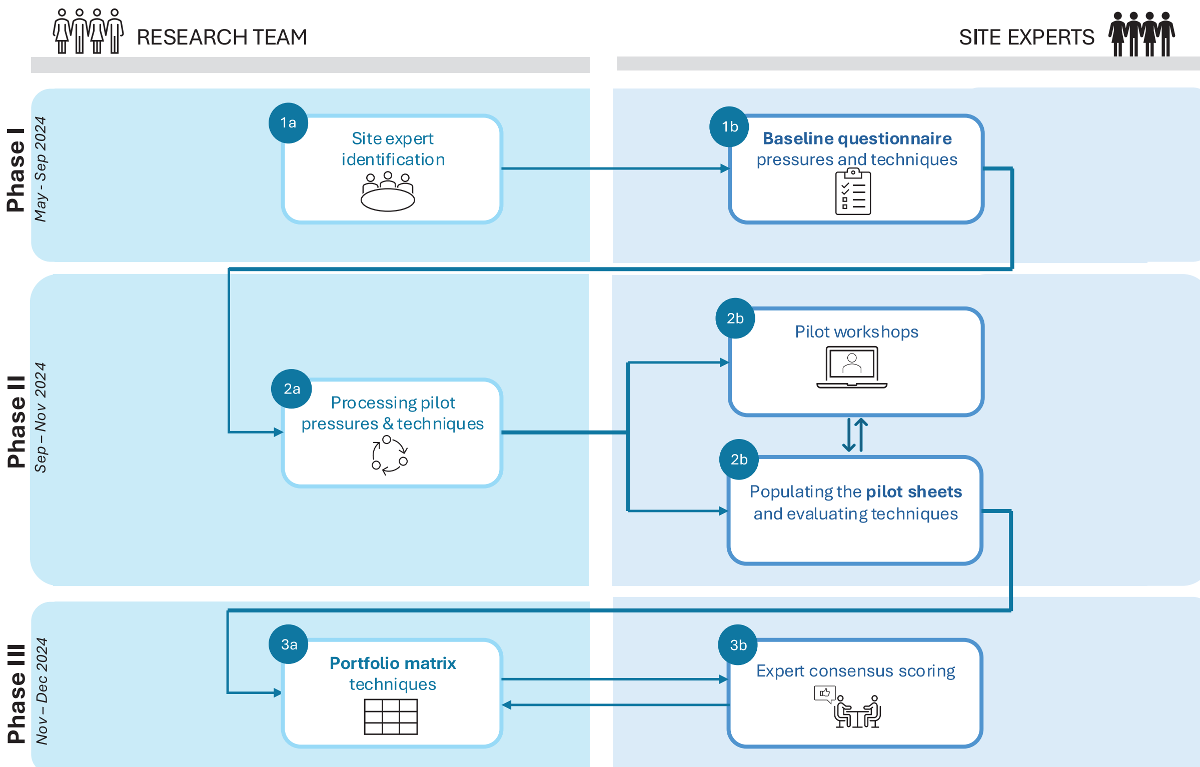

Fig. 2. Methodological workflow of the augmented Delphi method to engage the site experts.

differences in performance among the gray, green, and hybrid restoration techniques. Prior to analysis, data distribution was verified using the Shapiro–Wilk test, and homogeneity of variances was assessed using the Levene test to check for the assumptions to perform a one-way analysis of variance (ANOVA). When normality and variance homogeneity were not met, a non-parametric Kruskal-Wallis test was applied instead of ANOVA, ensuring the robustness of the comparisons among NBS categories.

In order to evaluate the level of agreement between experts, overcome variations among experts' opinions, and reduce bias, the third and final phase of this work involved all participants. Understanding whether diverging judgments reflect systematic differences in expert fields of experience is critical for building confidence (Dorrough et al., 2025). The experts were asked to rate their level of agreement regarding the applicability of each restoration technique to mitigate the pressures, using a 1-to-5 Likert scale (Likert, 1932), where 1 represents complete disagreement and 5 represents complete agreement. The resulting scores were averaged and standard deviations were calculated as a proxy of the uncertainty level (Campagne and Roche, 2018), thus variability reflects context-dependent expertise rather than inconsistency.

2.2.4. Development of the interactive digital tool

All the collected data were subsequently organized into a structured dataset, which serves as input for a Shiny application developed using R language (v. 4.3.3, R Core Team, 2021; *Shiny* package by Chang et al., 2025), and deployed via *rsconnect* (Atkins et al., 2025). The application can be accessed directly through a web-based graphical user interface, or run locally on a computer by following the instructions and the .R script included in SM III. The tool provides a dropdown menu that allows the user to select an environmental pressure they are interested to mitigate. Based on this selection, a list of restoration techniques that have been implemented and evaluated as a potential technique to address that pressure is displayed. Each restoration technique is briefly described, and by clicking on its name, the user can view the level of agreement regarding the adequacy of that restoration technique according to the interviewed experts, as well as two radar charts showing the scores obtained by the technique in terms of their structural characteristics and their relevance in fostering natural processes. The Shiny-based decision-support tool was iteratively tested for usability and reliability. Usability was verified through internal pilot testing by the research team and external feedback from practitioners involved in the pilot sites, who reviewed the clarity of interface elements and the flow of interactive filters. Reliability was assessed by cross-checking and comparing the tool's graphical outputs with the underlying datasets to confirm consistency and data integrity. Minor interface adjustments were introduced based on user feedback to enhance accessibility and interpretability across platforms. The open-source nature of the application ensures that new information can be integrated in the future as additional research is conducted.

3. Results: Expert-based assessment of restoration techniques

3.1. Diverse anthropogenic and natural pressures shaping EU coastal marine regions

The results of the questionnaire indicate that case studies are subject to a wide range of natural or climatic and anthropogenic pressures, reflecting the varied environmental and socio-economic contexts in which they are situated, while also revealing commonalities between the EU coastal marine regions. Anthropogenic pressures account for 42% of the total pressures identified, with pollution, nutrient loading and eutrophication being the most frequently reported. Conversely, natural pressures accounted for the minority of the identified pressures; however, natural responses to anthropogenic stressors accumulated in 53.4% of the reported pressures. The specific pressures indicated by the experts for each of the pilot sites are included in the site sheets (SM II). The spatio-temporal characteristics of the pressures, as described by the site experts, reveal a lengthy onset and extensive impact across the regions. The majority of the site pressures have been experienced for multiple decades (71.9%), often occurring in trends and patterns with similar negative effects on the ecosystem. Many pressures are widespread and affect a large spatial area (49.3%), and along with the long temporal onset of these pressures, these impacts likely reflect an interconnection with broader climate dynamics.

During the discussions, it emerged that each pilot, being part of complex socio-environmental systems, is subject to pressures that affect the ecological aspect of the site. The primary impact mentioned in combination with these pressures is the loss of habitat and biodiversity due to the altered suitability and quality of the habitat. However, other impacts mentioned by the site experts often represent secondary derived pressures, which in the long term can lead to further impacts. These are not caused solely by the primary pressures, and the resulting effects are not necessarily traceable to the initial pressure but rather to the combined and emerging effect of the chain and interactions of different pressures. For this reason, moving forwards, the pressures have been considered as if they were simultaneously both pressures and impacts, following the logic of Imp-Press (sensu Segurado et al., 2014), namely pressures that are strongly linked to impact and likely triggering feedback loops with other pressures and further impacts.

3.2. Characteristics of restoration techniques

The site experts highlighted how wide the spectrum of restoration techniques may be, ranging from i) strictly green techniques relying only on natural materials and processes: wood bundles (fascines), oyster reefs, seagrass transplantation; ii) hybrid techniques merging gray and green, for instance through wave breakers, or culverts, to iii) gray techniques supporting greening based on engineering techniques, like the reshaping of channels to restore the natural connectivity, artificial island rims with metallic sheet piles, or building a barrier to regulate the water levels for biodiversity purposes. Overall, 49 restoration techniques have been evaluated (13 green, 11 Gray, and 25 Hybrid techniques). The characteristics of each restoration technique can be explored through the interactive digital tool developed for this work (SM III, app interface also available at https://ecological.shinyapps.io/coastal_restoration_tool/).

Some common patterns emerged from the overall analysis of the features and the scoring of the restoration techniques (Fig. 3). The ability of different solutions to support biogeochemical cycles, geomorphological processes, and morphological support varied according to the experts, reflecting the distinct mechanisms underlying several gray, hybrid, and green interventions. Statistical analyses, however, did not reveal significant differences among categories for either the "structural characteristics" or the "natural processes"

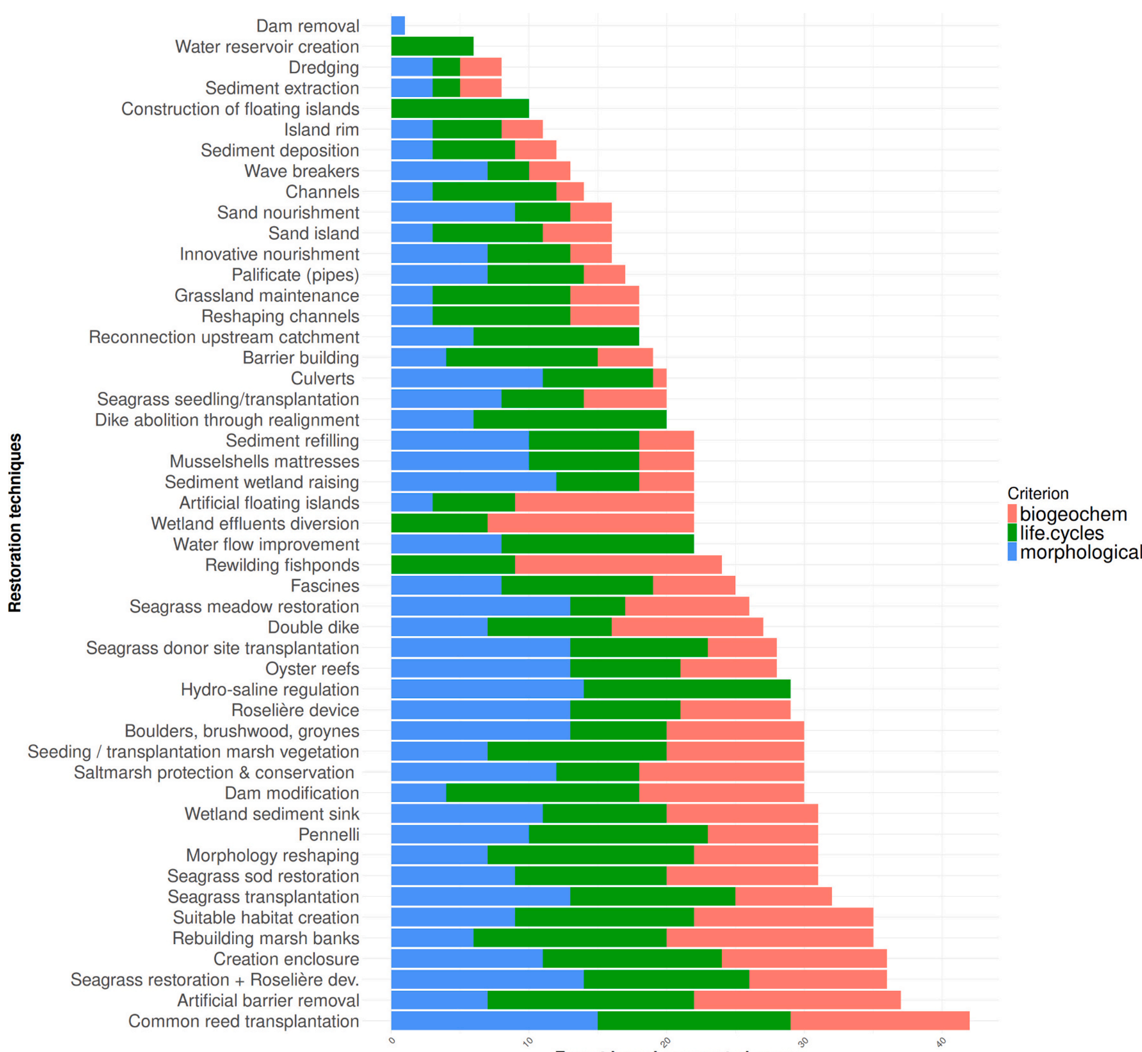

Fig. 3. The potential performance of the restoration techniques, as evaluated by the local experts, in supporting or enhancing the natural processes aggregated into three categories, namely, biogeochemical support, life cycles support, and geomorphological processes.

(described in Section 2.2.2.) composite indices (Kruskal-Wallis chi-squared = 0.22, p = 0.89; ANOVA F = 2.619, p = 0.08, respectively). Despite the lack of statistical significance, both analyses indicate a consistent trend in which green solutions tend to outperform hybrid and gray interventions, particularly for the maintenance of geomorphological and biogeochemical processes. This pattern is ecologically consistent with the higher degree of naturalness and self-regulation expected from green restoration techniques, such as *Phragmites australis* transplantation, seagrass planting, and sodding, which contribute to multiple process-based functions simultaneously. In contrast, more engineered approaches (e.g., dam removal, revetments, sediment trapping structures) tend to focus on morphological stabilization while having limited or delayed influence on biogeochemical or life-cycle processes. The variability observed within hybrid and gray categories likely reflects their context-specific design and implementation conditions across sites.

At the same time, the site experts scored the restoration technique's structural characteristics using the indicators described in section 2.2.2 to provide insights into the aggregated sustainability, velocity, spatial scale and longevity categories of the techniques across the case studies. The time needed for the restoration techniques to achieve structural stability varied significantly, ranging from days to a few years, with 80% of the techniques needing a few months or more. Similarly, the time required for the techniques to start delivering the principal processes for which they were created was scored between a few days and a few years, showing a similar pattern with 70.8% of the NBS-techniques starting to deliver the principal processes for which they were created after a few months or more. It should be noted that no significant difference was observed in terms of time taken to stabilize between gray, hybrid and green solutions, although overall gray solutions on average seem to have a higher velocity. The longevity of the techniques, a critical factor for long-term performance, was estimated to span from a very short to a very long time, with 60% of the techniques categorized as having a long or very long longevity. Regarding materials, 67.5% of the techniques are constructed using mostly or only locally sourced materials, of which 40.9% employed most or all biodegradable materials. Moreover, when looking at the sustainability category, green solutions scored significantly higher than gray and hybrid solutions (ANOVA F = 4.994, p-value = 0.011), indicating an overall higher use of sustainable materials for green solutions (Post-hoc pairwise comparisons through Tukey test p = 0.009 between green and gray solutions). Fig. 4 shows the aggregated structural indicators pertaining to the potential overall performance of the techniques, that have been evaluated under the structural perspective and the speed with which they can be implemented and reach structural stability.

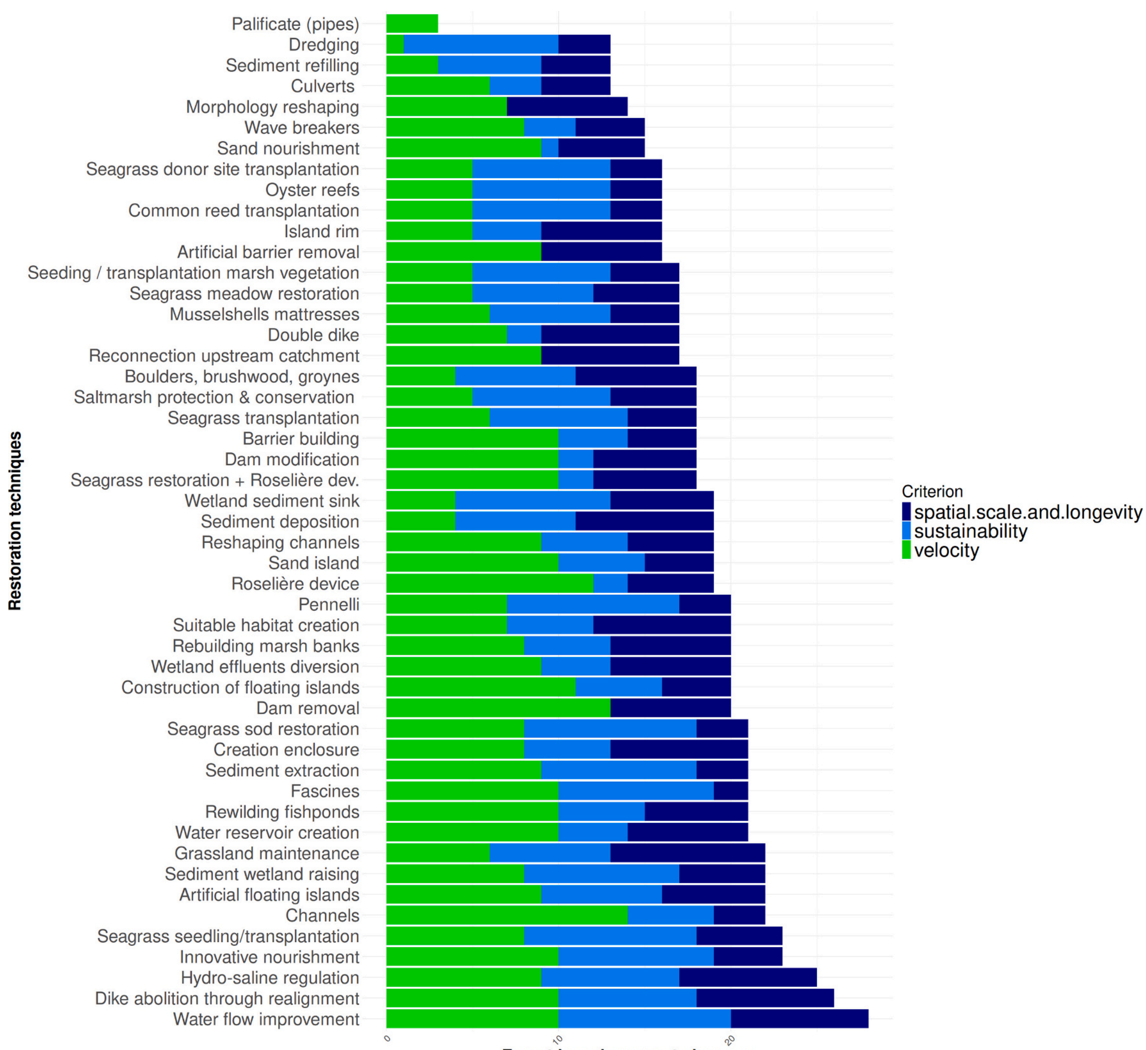

Fig. 4. The potential performance of the restoration techniques in structural terms, represented by the scores assigned by local experts aggregated into three categories: spatial scale and longevity, sustainability, and velocity.

3.3. Expert assessment of restoration performance across environmental pressures

The heat map illustrates the impact of a low, medium and high intensity hypothetical scenario for each pressure on the identified restoration techniques (Fig. 5), highlighting where each technique is most effective and where it might be less suitable due to pressures impacting their structural stability and, consequently, their capability to foster the natural processes and functions they are expected to support effectively. As the pressure intensity increases, from low to high, a clear trend emerges where the techniques become more affected by the respective pressures. Specific techniques, including oyster reefs, common reed transplantation, seagrass transplantation and wetlands as sediment sinks, seem to be strongly impacted already at low intensity pressures, including storm intensification, relative sea level rise, drought, sediment deficits, coastal erosion, and dredging. On the other hand, a variety of techniques show low sensitivity to pressures, including dam removal and modification, floating islands and their rims, and water reservoir creation. The heatmap also reveals that storm intensification, followed by relative sea level rise, exerts large impacts across the multiple techniques, particularly under the medium and high scenarios.

In order to evaluate the techniques applicability in a broader sense, the experts were asked to give their evaluations on the applicability of the full list of techniques against all pressures using a Likert-scale,

Fig. 5. Heat map showing the impact of hypothetical pressures on the techniques as scored by site experts on a 0 to 5 scale. Missing values reflected non-applicability of the technique.

ranging from "strongly disagree" to "strongly agree". There is a general consensus regarding the performance of restoration techniques to mitigate pressures, showing that for turbidity, biodiversity loss and habitat loss, about 70% of the experts agree or strongly agree with the techniques capacity to mitigate the pressures, and even reaching 100% agreement for excess sediment (Table 2).

The experts participating in scoring revealed a particular high consensus regarding restoration-techniques such as saltmarsh protection and conservation (4.9 ± 0.4), or seagrass transplantation combined with the Rosalière device - a bio-inspired structure that mimics seagrass meadows and their hydrodynamic effect (Cognat et al., 2025)-to address habitat loss and biodiversity loss (4.8 ± 0.4 and 4.7 ± 0.5, respectively). On the other hand, the experts generally disagreed with the use of innovative nourishment to address biodiversity loss (2.1 ± 0.7), although they recognized the promising performance of the technique for mitigating or remediating the effects of other pressures. For pressures such as turbidity and excess sediments, experts reached a higher level of agreement on the performance of the subset of suitable techniques (4.2 ± 0.5 and 4.0 ± 0.7, respectively), whereas for excessive nutrient loading opinions were more divided (3.7 ± 1.2). Variations in scoring of techniques to mitigate certain pressures may stem from differences in expertise, context-specific processes or experiences, and the subjectivity inherent in evaluations.

4. Discussion & conclusion

Coastal adaptation needs to be a holistic, strategic and adaptive process to effectively address the negative effects of increasing pressures (Tobey et al., 2010). One of the recommended approaches for achieving this adaptive pathway is the focus on mainstreaming ecological restoration in coastal areas, with the aim to support natural processes, enhance ecosystem resilience through maintaining ecological functions, and address the effects of impacts and pressures affecting marine, estuarine, and transitional waters ecosystems. This strategy becomes particularly relevant in areas dominated by human presence, where human activities and the ecological structures evolved together, up to the point that while humans depend on the ecosystem, the preservation of such ecosystems often appears to be highly dependent on human efforts (Stocco and Pranovi, 2023). In this context, a clear selection of the objectives and the design of the restoration is imperative for the success of the intervention (Hudson et al., 2021), relating not only to the purpose of the implemented measure but also to the ecological context (Pérez et al., 2024). It is well established that human pressures are causing a wide array of damaging impacts across the globe (Chausson et al., 2020), and have significantly expanded in recent decades due to human influences (Borja et al., 2024). Given the urgency of restoration actions in the EU coastal zones, selecting the right solutions and designing appropriate interventions is imperative. However, despite this urgency, restoration solutions are still not well known, and the scarcity of data presents a challenge to rapid and effective implementation (O'Leary et al., 2023). To enable a more robust and swift implementation of restoration techniques along river-to-sea continuums without avoidable errors, organizing a collection of already tested techniques for selection under various pressures can support a screening phase to avoid implementing those that might be irrelevant or unable to withstand this particular pressure over time. This process, in addition to contributing to mainstreaming the choice of restoration interventions, increases the likelihood of selecting the most suitable technique among those with the right characteristics for a specific issue and ecosystem, thereby enhancing the chances that the restored ecosystem will continue to deliver the desired processes (Webster et al., 2017). Expert-based approaches have proven valuable in the literature (e.g., Waring, 2024; Seijger et al., 2014; Khodyakov et al., 2023), particularly when timely decision-making is needed and long-term experimental validation is not feasible.

Capitalizing on the obtained expert-based knowledge gathered from 9 sites in the EU coastal region, we argue that the implementation of coastal restoration can be facilitated thanks to evidence-based functional and structural design guidance (Montanari, 2017), and that building on the site specific insights can facilitate the transferability and upscaling of restoration. The collocation of these findings into a restoration portfolio considering various ecological and pressure contexts, provides a general guide for coastal adaptation that ought to be balanced with site specific considerations. Other decision-supporting tools based on the results of already experimented approaches and the relevant considerations of local experts have been successfully implemented in the past, e.g. to guide nourishments in coastal areas, including tools that help choosing the most effective coastal protection structures (APAT, 2007; Riggio et al., 2006). Expert-based approaches are certainly beneficial when addressing a complex environmental issue is a priority task since they are quick to implement, allowing for fast results even when data from traditional scientific experiments are still lacking due to the short time passed since the testing phase of promising restoration techniques.

The results obtained by involving local experts, with different expertise and backgrounds, underlined the positive perception on the performance of some well-known green restoration interventions, including seagrass and macrophyte transplantation and saltmarsh restoration. For well-known green restoration techniques, a broad range of literature corroborates the expert scoring in this work, including large review efforts that collect evidence on the performance of seagrass restoration techniques in the Mediterranean (e.g., Pansini et al., 2022; Boudouresque et al., 2021). On a smaller scale, the Venice Lagoon has a long history of saltmarsh restoration, providing insight in the applicability of various techniques based on the saltmarshes' nature and the pressures afflicting the habitat (Tagliapietra et al., 2018; Bonometto, 2003). However, while the green techniques described in this study offer significant potential to address coastal pressures by enhancing the natural processes that leverage ecosystem resilience and deliver multiple benefits, it has also become evident that their performance can be constrained when impacts and pressures become too intense, as also highlighted by other authors (Saunders et al., 2020). This was observed for most of the restoration techniques included in this study, regardless of being green, hybrid, or gray, where their performance was indicated to be compromised by increasing pressure intensity, emphasising the need for complementary strategies.

In the case of green techniques, which also include Nature-based solutions, the vulnerability might relate to the fact that green techniques rely on morphological and ecological processes, e.g. sedimentation, nutrient uptake, carbon sequestration, that might be disrupted by

Table 2
Expert agreement on the performance of restoration techniques to mitigate various pressures. It should be noted that not each category of pressures contains the same amount of available restoration techniques. Full scoring available via the digital tool in SM III.

	Turbidity	Sediment loss	Habitat loss	Excessive sediment	Excessive nutrient loading	Erosion risk	Biodiversity loss
Strongly disagree	0 (0%)	0 (0%)	0 (0%)	0 (0%)	4 (7.4%)	0 (0%)	1 (0.9%)
Disagree	0 (0%)	0 (0%)	10 (6.4%)	0 (0%)	6 (11.1%)	1 (1.4%)	12 (10.5%)
Neither disagree nor agree	1 (16.6%)	3 (50%)	36 (23.7%)	0 (0%)	9 (16.7%)	26 (36.1%)	22 (19.3%)
Agree	3 (50%)	2 (33%)	51 (32.7%)	3 (100%)	12 (22%)	23 (31.9%)	39 (34.2%)
Strongly agree	2 (33.3%)	1 (16.7%)	59 (37.8%)	0 (0%)	23 (42.6%)	22 (30.5%)	40 (35.1%)

strong pressures. On the other hand, a variety of hybrid and gray techniques show low sensitivity to pressures because they include robust engineering materials, built to endure specific physical pressures that are less dependent on ecological conditions and processes. These techniques are especially deployed in cases where there is the need for layering interventions by integrating ecology with engineering, in a way that can assist in developing a regenerative design solution that can adapt to climate change, enhance the local ecosystem, and protect valuable communities (Dunlop et al., 2023). This approach involves creating bundles of solutions that harmonize gray infrastructure with Nature-based strategies, leveraging their combined strengths to achieve sustainable and resilient outcomes (EC, 2025) especially when nature has been so severely compromised in its ecological structure and functioning that it requires intensive restoration actions to ensure its conservation. In such cases, gray techniques are seen as a necessary support to green solutions for achieving an effective restoration. Similarly, when hybrid gray-green approaches blend strategic uses of “natural” landscapes with gray human-engineering structures, this has the capacity to underpin morphological and ecological perspectives, as it is the case highlighted in this study such as dam modifications or removal, barrier destruction, and renaturalization of landscape elements through sediments recycling and channels reshaping. Additionally, blending different methodologies is generally regarded as a better approach than just implementing gray solutions, in cases when adjustments might be needed. For instance, in the Rhône Delta case study, it has been highlighted that recent changes in pressures have shifted the focus from classical hard coastal protection to the need of incorporating more Nature-based interventions (Sabatier et al., 2009). The realignment through dike abolition, as well as the dike breaches establishing a reconnection to the upstream catchment are examples of these types of blended strategies. Such hybrid solutions, through focusing on ecosystem management by removing the interruptions to water flow or providing the opportunity to trigger water flow, have been assessed as valuable approaches to conserve ecosystem functions and values in this pilot as well as in others, thus confirming the findings of other authors (e.g., Kuwae and Crooks, 2021). In these cases, the priority is to harness self-facilitation by removing obstacles or by using temporary or permanent structures or techniques, e.g. floating islands or the use of natural materials, to trigger and support the processes that generate self-facilitation and enhance restoration success through the explicit or implicit imitations of emergent traits of a functioning, persistent ecosystem (Temmink et al., 2023).

The differences between pilots and the variety of different expertise and backgrounds of the experts represented a good opportunity for cross-regional learning and sharing of best practices, providing both formal and informal exchanges that are more responsive to the needs of stakeholders and extend benefits beyond the individual sites (Maher et al., 2022). A variety of techniques have been analysed in multiple case studies, and despite the recent application of the restoration techniques, the expert-based evaluations allowed for obtaining a set of interactive tools that have the potential to support the decision-making process for restoration and adaptation upscaling and exportability. The positive sides of applying expert judgment for the assessment presented in this study that are the final outcome benefits from the local experts' deep understanding of the challenges faced by coastal areas today. As a result, the restoration techniques database, along with the scoring of the techniques and the heatmap matrix that try to forecast how each technique would evolve and perform in scenarios with different future pressure conditions, can be considered broadly applicable. This approach is aligned with recent contributions from large-scale EU projects focused on coastal resilience and digital tools for restoration assessment (e.g., REST-COAST, EDITO, and national initiatives, e.g. Staneva et al., 2024; Jacob et al., 2023; Chen et al., 2024; Marijnissen, 2021). The results help identify potentially suitable restoration techniques for specific environmental contexts and pressure conditions, thereby supporting decision-making in selecting and implementing restoration techniques in varying pressure scenarios. Moreover, the expert-based evaluation provides synthetic assessments that simplify complex data, making it easier to synthesize key findings and then communicate them key findings to a broad audience, and offering concise insights that can be quickly shared across various stakeholders, which aids in decision-making and policy development.

However, since the sites and the experts were of limited numerosity and there is the need to consider the risk of biased or limited knowledge due to the experts' familiarity with specific environments. Factors such as limited knowledge of newer techniques, uncertainty about pressure dynamics, and diverse site characteristics further contribute to differing assessments. This is evidenced by the large variation observed in agreement for some pressures, which may be attributed to the limited expertise on this particular topic in the pool of experts consolidated during this work.

This evaluation ultimately highlights that the most effective restoration techniques are highly site-specific and that, under extreme pressures, gray solutions may complement green solutions, when necessary. It has also been underscored that in some areas no intervention can address the multiple negative effects of combined pressures and impacts, especially when it comes to pressures originated by human activities: in such cases, gray solutions blended within natural landscapes are commonly implemented to quickly counteract environmental issues. Such an approach is commonly considered acceptable, since tackling 21st-century challenges might require innovative solutions that utilize all available tools (Doswald et al., 2021; Sutton-Grier et al., 2015). However, this also raises the critical dilemma of the willingness to find integrated solutions to quickly address the negative effects of anthropogenic pressures on ecosystems, while the same sources of pressures still go unmanaged. While climate change pressures present immense challenges, and mitigation or adaptation are generally favored, for coastal ecosystems that are threatened by anthropogenic pressures it may be more appropriate to first consider reducing the pressures we still control, and then resorting to restoration interventions. This is particularly true when green solutions are deemed insufficient, and there is a necessity to turn to hybrid or gray solutions. Only by doing so, we can create conditions where green becomes viable and contribute to restoration in a more nature-like and sustainable way.

Additionally, since it might be impossible to eliminate the negative consequences of all pressures, even through massive and widespread restoration (Singhvi et al., 2022), it is crucial to focus on reducing pressures in the ecosystems by managing the coastal space and working on holistic adaptation leveraging stakeholder knowledge and awareness. Decreasing pressures in coastal areas will allow for easier reinitialization of ecosystem processes toward a more natural unstressed state (Simenstad et al., 2006), thus enhancing not only the natural recovery capacity of the ecosystems but also the benefits from restoration. This aspect surely represents a key area for future exploration, likely starting from approaches of various numerical simulations and ecological modeling studies, such as those conducted to assess the functioning of double dike system in the Wadden Sea case (Marijnissen et al., 2021), seagrass as NBS for coastal protection (Jacob et al., 2023; Chen et al., 2024; Villa Castrillón et al., 2025), and dunes vegetation capacity to mitigate flooding in the Sicily Cuba-Longarini Lagoon (Musumeci et al., 2023; Marino et al., 2025), designed to forecast the performance of the techniques not only under current, but also future conditions.

Another frontier of research is triggered by the fact that this study collected information and assessment by expert-based approaches. While offering quick answers and valuable insights for upscaling and generalization, the results should be seen as preliminary assessments and considered just as a starting point to inspire future research - which is another reason to support the development of a decision-making support tool which is participatory, open-source and expandable. Indeed, as all the approaches that do not include high-resolution measures in the field or gauged within controlled enclosures, tools based on experts' opinions might incur the risk of overlooking the complex synergies and emergent behaviors between combined restoration techniques and natural processes, as well as the feedback loops due interactions between combined pressures and impacts. Understanding these dynamic relationships is essential for future implementation of multiple restoration techniques in fragile environments, which might be facing more than one pressure at a time. Coordinating the management of restoration projects, and evaluating their collective effectiveness, requires therefore a deeper understanding of how ecosystems are impacted by changing spatial patterns, cross-boundary effects, and spatial crowding across the landscape (Diefenderfer et al., 2021).

Likewise, considering the complexity of multiple effects caused by various impacts and pressures, implementing approaches for managing restoration and adaptation will require regional leadership and collaborations between conservation non-governmental organizations, academic researchers, governments and other public and private local stakeholders. In many cases, collaboration would likely span political boundaries to be successful, requiring transnational conservation strategies and agreements (Webster et al., 2017). Although true for all coastal regions, this is particularly important for cross-boundary pilot cases that need to align not only the restoration interventions, but also their policy and ecosystem-based management strategies and restoration interventions to effectively decrease and mitigate the pressures which affect shared watersheds, stocks as well as the coasts. Future efforts should continue to build on cross-regional insights and ensure that evolving tools - such as Digital Twins and high-resolution forecasts - are coupled with ecological monitoring and stakeholder feedback (Pillai et al., 2022; Jacob et al., 2023; Sánchez-Arcilla et al., 2022).

In this regard, one of the contribution of this work is based on the development of the open-source digital tool, hosted in an open-access repository which is open to contribution and further implementations, lays the basis to validate and keep building up in the scientific community the knowledge, by allowing additional experts and researchers studying different ecosystems and pilot sites to contribute in advancing knowledge of restoration techniques in the future. This could also allow for a more systematic analysis of the experts' consensus, to be considered in future improvements of the investigation in the field. With the aim to overcome the potential bias in expert judgment, the tool will indeed serve as a dynamical platform that can integrate additional data from future pilot projects and other case studies, enhancing the collective understanding of restoration solutions across diverse ecological and socio-economic contexts. Moreover, in the future, such a tool could benefit from the inclusion of additional evaluation parameters and socio-economic characteristics affected by and influencing these restoration techniques for a more holistic evaluation of their performance. While qualitative pressure categories were used to ensure cross-context applicability in this study, the tool is designed to also incorporate quantitative thresholds (e.g., sea-level rise rates, sediment budgets, wave climate metrics) as consistent datasets may become available in future applications. Similarly, integrating information regarding socio-economic variables such as funding, cost-effective ratio and feasibility of restoration techniques would provide quantitative information that informs their viability, and therefore facilitates the uptake of restoration techniques. Having such a tool available can help decision makers to cope with the governance challenges because the tool interactively shows the interplay of restoration techniques and the pressures or the impacts to which coastal areas and wetlands along the river-to-sea continuums are affected. This way, the tool, once populated with further data, has the potential of supporting more expedited decision-making for coastal restoration efforts in the EU.

The combined approach used in this study has proven effective for leading toward the improvement of the design and implementation of restoration techniques in coastal areas and river-to-sea continuum, especially if applied and tested in other locations in the future. Strengthening such linkages between scientific knowledge and cross-pilot learning is key to scaling up restoration, enhancing the effectiveness of restoration approaches, and driving their adoption across the coastal regions (Vanderklift et al., 2020). These collaborations between different sites in the EU coastal marine regions could facilitate mutual learning and cooperation, both in developing strategies to reduce pressures on human-dominated coastal ecosystems and in sharing skills on specific restoration techniques. By supporting more robust design and implementation processes, this work contributes to the long-term goal of mainstreaming restoration within coastal risk reduction to address the challenges posed by climate change and the lasting impacts of human activities on these crucial ecosystems.

Authors contribution

Fabienne Horneman (F.H.) and Alice Stocco (A.S.) equally contributed to the delivery of this work and are designated as co-first authors. We kindly request that this information be included in the published version and in all citation formats.

CRediT authorship contribution statement

Fabienne Horneman: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alice Stocco:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paolo Comandini:** Writing – review & editing, Validation, Conceptualization. **Alberto Barausse:** Writing – review & editing, Conceptualization. **Nuno Caiola:** Writing – review & editing, Validation. **Agustín Sánchez-Arcilla:** Writing – review & editing, Project administration, Funding acquisition. **Vicente Gracia:** Writing – review & editing, Validation. **Richard Marijnissen:** Writing – review & editing, Validation. **Sara Pino Cobacho:** Writing – review & editing. **Luciana Villa Castrillón:** Writing – review & editing. **Joanna Staneva:** Writing – review & editing. **Elitsa Hineva:** Writing – review & editing. **Nataliya Andreeva:** Writing – review & editing. **Massimiliano Marino:** Writing – review & editing. **Rosaria Ester Musumeci:** Writing – review & editing, Supervision. **Julien Dalle:** Writing – review & editing, Validation, Funding acquisition. **Mathis Cognat:** Writing – review & editing. **Olivier Boutron:** Writing – review & editing, Funding acquisition. **Morgane Jolivet:** Writing – review & editing. **Avi Uzan:** Writing – review & editing. **Shiri Zemah-Shamir:** Writing – review & editing. **Gregorz Rozynski:** Writing – review & editing, Validation. **Elisa Furlan:** Conceptualization, Supervision, Writing – review & editing. **Ignacio Gatti:** Writing – review & editing. **Caterina Dabalà:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Fabio Pranovi:** Writing – review & editing, Supervision, Conceptualization. **Andrea Critto:** Writing – review & editing, Supervision. **Silvia Rova:** Writing – review & editing. **Silvia Torresan:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

Acknowledgements

This work has partially been funded from the European Union's Horizon 2020 Research and Innovation Action under Grant Agreement No°101037097 (EU- REST-COAST - https://rest-coast.eu/). The authors would like to acknowledge Dr. Elisa Furlan, Dr. Francesca Coccon, Dr. Ing, Pierpaolo Campostrini, Dr. Ing. Valerio Volpe, and Dr. Cristophe Briere, for their collaboration throughout the project. This study was partly carried out within the RETURN Extended Partnership (AB) and received funding from the EU's NextGenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE00000005).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2026.114629.

Data availability

All the data collected for this work are fully available and can be found among the Supplementary Materials.

References

Alvarez, S., Larkin, S.L., Ropicki, A., 2017. Optimizing provision of ecosystem services using modern portfolio theory. Ecosyst. Serv. 27, 25–37. https://doi.org/10.1016/j.ecoser.2017.07.016.

APAT, 2007. Atlante delle opere di sistemazione costiera 44/2007. Manuali e linee guida.

Atkins, A., Allen, T., Wickham, H., McPherson, J., Allaire, J., 2025. rsconnect: Deploy Docs, Apps, and APIs to 'Posit Connect', 'shinyapps.io', and 'RPubs'. R package version 1.3.4. https://github.com/rstudio/rsconnect. https://rstudio.github.io/rsconnect/.

Baeye, M., Fettweis, M., Voulgaris, G., et al., 2011. Sediment mobility in response to tidal and wind-driven flows along the Belgian inner shelf, southern North Sea. Ocean Dyn. 61, 611–622. https://doi.org/10.1007/s10236-010-0370-7.

Bayraktarov, E., Brisbane, S., Hagger, V., Smith, C.S., Wilson, K.A., Lovelock, C.E., Gillies, C., Steven, A.D.L., Saunders, M.I., 2020. Priorities and motivations of marine coastal restoration research. Front. Mar. Sci. 7 (July). https://doi.org/10.3389/fmars.2020.00484.

Bianciardi, A., Becattini, N., Cascini, G., 2023. How would nature design and implement nature-based solutions? Nat.-Based Solut. 3 (November 2022), 100047. https://doi.org/10.1016/j.nbsj.2022.100047.

Bonometto, L., 2003. ECOLOGIA APPLICATA e RIPRISTINO AMBIENTALE NELLA LAGUNA di VENEZIA: ANALISI e CLASSIFICAZIONE FUNZIONALE DELLE "BARENE" e DELLE TIPOLOGIE di INTERVENTO SULLE BARENE, pp. 1–235.

Borja, A., Elliott, M., Teixeira, H., Stelzenmüller, V., Katsanevakis, S., Coll, M., Galparsoro, I., Fraschetti, S., Papadopoulou, N., Lynam, C., Berg, T., Andersen, J.H., Carstensen, J., Leal, M.C., Uyarra, M.C., 2024. Addressing the cumulative impacts of multiple human pressures in marine systems, for the sustainable use of the seas. Front. Ocean Sustain. 1. https://doi.org/10.3389/focsu.2023.1308125.

Boudouresque, C.F., Blanfuné, A., Pergent, G., Thibaut, T., 2021. Restoration of seagrass meadows in the mediterranean sea: A critical review of effectiveness and ethical issues. Water (Switzerland) 13 (8), 1–34. https://doi.org/10.3390/w13081034.

Brady, S.R., 2015. Utilizing and adapting the Delphi method for use in qualitative research. Int J Qual Methods 14 (5), 1–6. https://doi.org/10.1177/1609406915621381.

Brook, R. K., & McLachlan, S. M. (2005). On using expert-based science to "test" local ecological knowledge. Ecol. Soc., 10(2), 0–3.

Burkhard, B., Maes, J., 2017. Mapping ecosystem services. Pensoft Publishers. https://doi.org/10.1016/s0166-4115(08)60011-4.

Campagne, S.C., Roche, P.K., 2018. May the matrix be with you! Guidelines for the application of expert-based matrix approach for ecosystem services assessment and mapping. One Ecosystem 3. https://doi.org/10.3897/oneeco.3.e24134.

Carstensen, J., Andersen, J.H., Gustafsson, B.G., Conley, D.J., 2014. Deoxygenation of the Baltic Sea during the last century. Proc. Natl. Acad. Sci. 111 (15), 5628–5633. https://doi.org/10.1073/pnas.1323156111.

Chang, W., Cheng, J., Allaire, J., Sievert, C., Schloerke, B., Xie, Y., Allen, J., McPherson, J., Dipert, A., Borges, B., 2025. Shiny: web application framework for R. R package version 1.10.0.9000. https://github.com/rstudio/shiny.

Chausson, A., Turner, B., Seddon, D., Chabaneix, N., Girardin, C.A.J., Kapos, V., Key, I., Roe, D., Smith, A., Woroniecki, S., Seddon, N., 2020. Mapping the effectiveness of nature-based solutions for climate change adaptation. Glob. Chang. Biol. 26 (11), 6134–6155. https://doi.org/10.1111/gcb.15310.

Chen, W., Staneva, J., Jacob, B., Sánchez-Artús, X., Wurpts, A., 2024. What-if nature-based storm buffers on mitigating coastal erosion. Sci. Total Environ. 928, 172247.

Cognat, M., Schubert, C., Lapinski, M., Fauvel, T., Ganthy, F., Dalle, J., 2025. Innovative Approaches to Zostera Seagrass Meadow Restoration in the Arcachon Basin: Biomimetic Solutions for Hydrodynamic Control (No. OOS2025–1321). Copernicus Meetings. Available at: https://www.researchgate.net/publication/393090465_Innovative_Approaches_to_Zostera_Seagrass_Meadow_Restoration_in_the_Arcachon_Basin_Biomimetic_Solutions_for_Hydrodynamic_Control. Last accessed on 19th November, 2025.

Cohen-Shacham, E., Walters, G., Janzen, C., Maginnis, S., 2016. Nature-Based Solutions to Address Global Societal Challenges. In: Nature-based solutions to address global societal challenges. IUCN International Union for Conservation of Nature. https://doi.org/10.2305/iucn.ch.2016.13.en.

Davies, C., Chen, W.Y., Sanesi, G., Lafortezza, R., 2021. The European Union roadmap for implementing nature-based solutions: A review. Environ Sci Policy 121 (April), 49–67. https://doi.org/10.1016/j.envsci.2021.03.018.

Diefenderfer, H.L., Steyer, G.D., Harwell, M.C., LoSchiavo, A.J., Neckles, H.A., Burdick, D.M., Johnson, G.E., Buenau, K.E., Trujillo, E., Callaway, J.C., Thom, R.M., Ganju, N.K., Twilley, R.R., 2021. Applying cumulative effects to strategically advance large-scale ecosystem restoration. Front. Ecol. Environ. 19 (2), 108–117. https://doi.org/10.1002/fee.2274.

Doswald, N., Janzen, S., Nehren, U., Santamaría, K., Vevest, J. S., Edbauer, L., Chavda, S., Sandholz, S., Renaud, F., Ruiz, V., Navaez, L., Yang, S., Mohil, D., Uzoski, D., Gerner, N., & Grey, C. (2021). Words Into Action - Nature Based Solutions for Disaster Risk Reduction. Available at: https://www.undrr.org/words-action-nature-based-solutions-disaster-risk-reduction Last accessed on 28 Oct 2025.

Dorrough, J., Travers, S.K., Val, J., Scott, M.L., Moutou, C.J., Oliver, I., 2025. Evaluating models of expert judgment to inform assessment of ecosystem viability and collapse. Conservation Biology 39 (2), e14370.

Dunlop, T., Glamore, W., Felder, S., 2023. Restoring estuarine ecosystems using nature-based solutions: towards an integrated eco-engineering design guideline. Sci. Total Environ. 873 (December 2022), 162362. https://doi.org/10.1016/j.scitotenv.2023.162362.

EC, 2025. Nature-based solutions. https://research-and-innovation.ec.europa.eu/research-area/environment/nature-based-solutions_en.

Elmgren, R., 2001. Understanding human impact on the Baltic ecosystem: changing views in recent decades. AMBIO: A journal of the human. Environment 30 (4), 222–231. https://doi.org/10.1579/0044-7447-30.4.222.

Faivre, N., Fritz, M., Freitas, T., de Boissezon, B., Vandewoestijne, S., 2017. Nature-based solutions in the EU: innovating with nature to address social, economic and environmental challenges. Environ. Res. 159 (December 2016), 509–518. https://doi.org/10.1016/j.envres.2017.08.032.

Gladstone-Gallagher, R.V., Hope, J.A., Bulmer, R.H., Clark, D.E., Stephenson, F., Mangan, S., Rullens, V., Siwicka, E., Thomas, S.F., Pilditch, C.A., Savage, C., Thrush, S.F., 2019. Old tools, new ways of using them: harnessing expert opinions to plan for surprise in marine socio-ecological systems. Front. Mar. Sci. 6 (November), 1–10. https://doi.org/10.3389/fmars.2019.00696.

Gobster, P.H., Schneider, I.E., Floress, K.M., Haines, A.L., Arnberger, A., Dockry, M.J., Benton, C., 2020. Understanding the key characteristics and challenges of pine barrens restoration: insights from a Delphi survey of forest land managers and researchers. Restor. Ecol. 29 (1). https://doi.org/10.1111/rec.13273.

Hayes, A.L., Heery, E.C., Maroon, E., McLaskey, A.K., Stawitz, C.C., 2018. The role of scientific expertise in local adaptation to projected sea level rise. Environ Sci Policy 87 (November 2017), 55–63. https://doi.org/10.1016/j.envsci.2018.05.012.

Hudson, R., Kenworthy, J., Best, M., 2021. Saltmarsh restoration handbook: UK and Ireland (issue November). https://catchmentbasedapproach.org/wp-content/uploads/2021/10/Saltmarsh_Restoration_Handbook_FINAL_20210311.pdf.

Huthnance, J., Weisse, R., Wahl, T., Thomas, H., Pietrzak, J., Souza, A.J., van Beusekom, J., 2016. Recent change—North Sea. In: North Sea Region Climate Change Assessment. Springer International Publishing, Cham, pp. 85–136.

Jacob, B., Dolch, T., Wurpts, A., Staneva, J., 2023. Evaluation of seagrass as a nature-based solution for coastal protection in the German Wadden Sea. Ocean Dyn. 73 (11), 699–727.

Jacobs, S., Burkhard, B., Van Daele, T., Staes, J., Schneiders, A., 2015. "The matrix reloaded": A review of expert knowledge use for mapping ecosystem services. Ecol. Model. 295, 21–30. https://doi.org/10.1016/j.ecolmodel.2014.08.024.

Jordan, P., Fröhle, P., 2022. Bridging the gap between coastal engineering and nature conservation?: A review of coastal ecosystems as nature-based solutions for coastal protection. In: Journal of Coastal Conservation, vol. 26, Issue 2. Springer, Netherlands. https://doi.org/10.1007/s11852-021-00848-x.

Khodyakov, D., Grant, S., Kroger, J., Gadwah-Meaden, C., Motala, A., Larkin, J., 2023. Disciplinary trends in the use of the Delphi method: A bibliometric analysis. PLoS One 18 (8 August), 1–11. https://doi.org/10.1371/journal.pone.0289009.

Kuwae, T., Crooks, S., 2021. Linking climate change mitigation and adaptation through coastal green–gray infrastructure: a perspective. Coast. Eng. J. 63 (3), 188–199. https://doi.org/10.1080/21664250.2021.1935581.

Lawrence, J., Bell, R., Blackett, P., Stephens, S., Allan, S., 2018. National guidance for adapting to coastal hazards and sea-level rise: anticipating change, when and how to change pathway. Environ Sci Policy 82 (December 2017), 100–107. https://doi.org/10.1016/j.envsci.2018.01.012.

Likert, R., 1932. A technique for the measurement of attitudes. Archives of psychology.

Maher, N., Salazar, C., Fournier, A., 2022. Advancing salt marsh restoration for coastal resilience: a learning exchange. Wetl. Ecol. Manag. 30 (5), 1033–1047. https://doi.org/10.1007/s11273-021-09841-5.

Marijnissen, R.J., 2021. Shared-Use of Flood Defences (Doctoral dissertation,. Wageningen University and Research.

Marijnissen, R.J.C., Kok, M., Kroeze, C., van Loon-Steensma, J.M., 2021. Flood risk reduction by parallel flood defences – case-study of a coastal multifunctional flood protection zone. Coast. Eng. 167 (April), 103903. https://doi.org/10.1016/j.coastaleng.2021.103903.

Marino, M., Nasca, S., Alkharoubi, A.I., Cavallaro, L., Foti, E., Musumeci, R.E., 2025. Efficacy of nature-based solutions for coastal protection under a changing climate: A modelling approach. Coast. Eng., vol. 198,, 104700.

Meier, H.M., Väli, G., Naumann, M., Eilola, K., Frauen, C., 2018. Recently accelerated oxygen consumption rates amplify deoxygenation in the Baltic Sea. J. Geophys. Res. Oceans 123 (5), 3227–3240. https://doi.org/10.1029/2017JC013686.

Montanari, A., 2017. Nature based solutions for coastal protection. https://www.albertomontanari.it/node/96.

Moraes, R.P.L., Reguero, B.G., Mazarrasa, I., Ricker, M., Juanes, J.A., 2022. Nature-based solutions in coastal and estuarine areas of Europe. Front. Environ. Sci. 10 (June), 1–12. https://doi.org/10.3389/fenvs.2022.829526.

Morris, R.L., Konlechner, T.M., Ghisalberti, M., Swearer, S.E., 2018. From grey to green: efficacy of eco-engineering solutions for nature-based coastal defence. Glob. Chang. Biol. 24 (5), 1827–1842. https://doi.org/10.1111/GCB.14063.

Mukherjee, N., Zabala, A., Huge, J., Nyumba, T.O., Adem Esmail, B., Sutherland, W.J., 2018. Comparison of techniques for eliciting views and judgements in decision-making. Methods Ecol. Evol. 9 (1), 54–63.

Murray, J.W., Jannasch, H.W., Honjo, S., Anderson, R.F., Reeburgh, W.S., Top, Z., Izdar, E., 1989. Unexpected changes in the oxic/anoxic interface in the Black Sea. Nature 338 (6214), 411–413.

Musumeci, R.E., Marino, M., Cavallaro, L., Foti, E., 2023. Does coastal wetland restoration work as a climate change adaptation strategy? The case of the south-east of Sicily coast. Coastal Eng. Proc. 37, 66. https://doi.org/10.9753/icce.v37.papers.66.

O'Leary, B.C., Fonseca, C., Cornet, C.C., Vries, M.B. De, Degia, A.K., Failler, P., Furlan, E., Garrabou, J., Gil, A., Hawkins, J.P., Krause-jensen, D., Le, X., Peck, M.A., Sousa, I., Tr, E., Roberts, C.M., 2023. Embracing nature-based solutions to promote resilient marine and coastal ecosystems. Nat.–based Solut. 3 (December 2022). https://doi.org/10.1016/j.nbsj.2022.100044.

Orsi, F., Geneletti, D., Newton, A.C., 2011. Towards a common set of criteria and indicators to identify forest restoration priorities: an expert panel-based approach. Ecol. Indic. 11 (2), 337–347. https://doi.org/10.1016/j.ecolind.2010.06.001.

Osinga, R., Danovaro, R., Debney, A., Pogoda, B., 2024. Editorial: restoration of coastal marine ecosystems. Front. Mar. Sci. 11 (September), 1–5. https://doi.org/10.3389/fmars.2024.1485162.

Ostojic, A., McGill, S.P., Shawler, J.L., Elkins, A.J., Brown, S.M., Tereszkiewicz, P.A., Dopsovic, R., 2025. Validating Sediment Budgets along the North Atlantic Coast Using the Updated Sediment Budget Calculator. US Army Engineer Research and Development Center,[Coastal and Hydraulics Laboratory].

Pansini, A., Bosch-Belmar, M., Berlino, M., Sarà, G., Ceccherelli, G., 2022. Collating evidence on the restoration efforts of the seagrass Posidonia oceanica: current knowledge and gaps. Sci. Total Environ. 851 (March), 158320. https://doi.org/10.1016/j.scitotenv.2022.158320.

Pérez, G., O'Leary, B.C., Allegri, E., Casal, G., Cornet, C.C., de Juan, S., Failler, P., Fredriksen, S., Fonseca, C., Furlan, E., Gil, A., Hawkins, J.P., Maréchal, J.P., McCarthy, T., Roberts, C.M., Trégarot, E., van der Geest, M., Simide, R., 2024. A conceptual framework to help choose appropriate blue nature-based solutions. J. Environ. Manag. 352 (November 2023). https://doi.org/10.1016/j.jenvman.2023.119936.

Pillai, U.P.A., Pinardi, N., Alessandri, J., Federico, I., Causio, S., Unguendoli, S., Staneva, J., 2022. A digital twin modelling framework for the assessment of seagrass nature based solutions against storm surges. Sci. Total Environ. 847, 157603.

Pittman, S.J., Stamoulis, K.A., Antonopoulou, M., Das, H.S., Shahid, M., Delevaux, J.M. S., Wedding, L.M., Mateos-Molina, D., 2022. Rapid site selection to prioritize coastal seascapes for nature-based solutions with multiple benefits. Front. Mar. Sci. 9 (April), 1–23. https://doi.org/10.3389/fmars.2022.832480.

R Core Team, 2021. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Riggio, C., De Piccoli, R., Di Maggio, L., Valentini, F., Giangreco, R., Sorgente, B., Cappucci, S., Colonna, P., Petrillo, A., Randazzo, G., Paltrinieri, D., Russo, F., Corsini, S., Barbano, A., 2006. Gruppo di lavoro della Direzione Generale per la Difesa del Suolo del Ministero dell'Ambiente e della Tutela del Territorio. In: DOCUMENTO PRELIMINARE PER L'INDIVIDUAZIONE DEGLI INDIRIZZI E DEI CRITERI PER LA DIFESA DELLE COSTE. Available online at https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://cms.aubac.it/sites/default/files/2023-12/PRESENTAZIONE_DocPreliminareDifesacoste.pdf&ved=2ahUKEwi0_-a0zMaQAxUv8LsIHWw3BxgQFnoECBsQAQ&usg=AOvVaw2jnULpaCaupblSr3zq-pej. Last accessed on 28 Oct. 2025.

Sabatier, F., Samat, O., Ullmann, A., Suanez, S., 2009. Connecting large-scale coastal behaviour with coastal management of the Rhône delta. Geomorphology 107 (1–2), 79–89. https://doi.org/10.1016/j.geomorph.2006.09.026.

Sánchez-Arcilla, A., Cáceres, I., Roux, X. Le, Hinkel, J., Schuerch, M., Nicholls, R.J., Otero, del, M., Staneva, J., de Vries, M., Pernice, U., Briere, C., Caiola, N., Gracia, V., Ibáñez, C., Torresan, S., 2022. Barriers and enablers for upscaling coastal restoration. Nat.-Based Solut. 2 (September), 100032. https://doi.org/10.1016/j.nbsj.2022.100032.

Sarabi, S., Han, Q., de Vries, B., Romme, A.G.L., Almassy, D., 2022. The nature-based solutions case-based system: A hybrid expert system. J. Environ. Manag. 324 (October), 116413. https://doi.org/10.1016/j.jenvman.2022.116413.

Saunders, M.I., Doropoulos, C., Bayraktarov, E., Babcock, R.C., Gorman, D., Eger, A.M., Silliman, B.R., 2020. Bright spots in coastal marine ecosystem restoration. Current Biology 30 (24), R1500–R1510.

Saunders, M.I., Cannard, T., Fischer, M., Sheppard, M., Twomey, A., Morris, R., Bishop, M.J., Mayer-Pinto, M., Malcolm, F., Vozzo, M., Steven, A., Swearer, S.E., Lovelock, C.E., Pomeroy, A.W.M., McLeod, I., Waltham, N.J., 2024. A roadmap to coastal and marine ecological restoration in Australia. Environ Sci Policy 159 (February), 103808. https://doi.org/10.1016/j.envsci.2024.103808.

Schmitt, A., Chaumillon, E., 2023. Understanding morphological evolution and sediment dynamics at multi-time scales helps balance human activities and protect coastal ecosystems: an example with the Gironde and Pertuis Marine Park. Sci. Total Environ. 887, 163819. https://doi.org/10.1016/j.scitotenv.2023.163819.

Segurado, P., Almeida, C., Neves, R., Ferreira, M.T., Branco, P., 2018. Understanding multiple stressors in a Mediterranean basin: Combined effects of land use, water scarcity and nutrient enrichment. Science of the total environment 624, 1221–1233.

Seijger, C., van Tatenhove, J., Dewulf, G., Otter, H.S., 2014. Responding to coastal problems: interactive knowledge development in a us nature restoration project. Ocean Coast. Manag. 89, 29–38. https://doi.org/10.1016/j.ocecoaman.2013.12.011.

Shumway, N., Bell-James, J., Fitzsimons, J.A., Foster, R., Gillies, C., Lovelock, C.E., 2021. Policy solutions to facilitate restoration in coastal marine environments. Mar. Policy 134. https://doi.org/10.1016/j.marpol.2021.104789.

Simenstad, C., Reed, D., Ford, M., 2006. When is restoration not? Incorporating landscape-scale processes to restore self-sustaining ecosystems in coastal wetland restoration. Ecol. Eng. 26 (1), 27–39. https://doi.org/10.1016/j.ecoleng.2005.09.007.

Singhvi, A., Luijendijk, A.P., van Oudenhoven, A.P.E., 2022. The grey – green spectrum: A review of coastal protection interventions. J. Environ. Manag. 311 (March), 114824. https://doi.org/10.1016/j.jenvman.2022.114824.

Stanev, E.V., Peneva, E., Chtirkova, B., 2019. Climate change and regional ocean water mass disappearance: case of the Black Sea. J. Geophys. Res. Oceans 124 (7), 4803–4819. https://doi.org/10.1029/2019JC015076.

Staneva, J., Pinardi, N., Coppini, G., Jacob, B., Chen, W., Jayson-Quashigah, P.N., Drillet, Y., 2024. Advancing Marine Sustainability through Digital Twin What-If Scenarios in Nature Based Solutions. In: EGU General Assembly Conference Abstracts, p. 14266.

Stocco, A., Pranovi, F., 2023. The paradoxical need for human intervention in the conservation of natural environments in Venice lagoon. Sci. Rep. 13, 6798. https://doi.org/10.1038/s41598-023-33754-3.

Sutton-Grier, A.E., Wowk, K., Bamford, H., 2015. Future of our coasts: the potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. Environ Sci Policy 51, 137–148. https://doi.org/10.1016/j.envsci.2015.04.006.

Tagliapietra, D., Baldan, D., Barausse, A., Buosi, A., Curiel, D., Guarneri, I., Pessa, G., Rismondo, A., Sfriso, A., Smania, D., Volpi Ghirardini, A., 2018. Protecting and restoring the salt marshes and seagrasses in the lagoon of Venice. http://journal.um-surabaya.ac.id/index.php/JKM/article/view/2203.

Temmink, R.J.M., Angelini, C., Verkuijl, M., van der Heide, T., 2023. Restoration ecology meets design-engineering: mimicking emergent traits to restore feedback-driven ecosystems. Sci. Total Environ. 902 (April), 166460. https://doi.org/10.1016/j.scitotenv.2023.166460.

Tobey, J., Rubinoff, P., Robadue, D., Ricci, G., Volk, R., Furlow, J., Anderson, G., 2010. Practicing coastal adaptation to climate change: lessons from integrated coastal management. Coast. Manag. 38 (3), 317–335. https://doi.org/10.1080/08920753.2010.483169.

Toumbourou, T.D., Grover, S., Arifanti, V.B., Budiningsih, K., Idrus, N.I., Lestari, S., Rachmanadi, D., Sakuntaladewi, N., Salminah, M., Treby, S., Winarno, B., Yuwati, T. W., Ramawati, & Rawluk, A., 2024. Identifying a shared vision for peatland restoration: adapting the Delphi method to enhance collaboration. Mres Peat 30 (January). https://doi.org/10.19189/MaP.2023.OMB.Sc.2009692.

Vanderklift, M.A., Doropoulos, C., Gorman, D., Leal, I., Minne, A.J.P., Statton, J., Steven, A.D.L., Wernberg, T., 2020. Using propagules to restore coastal marine ecosystems. Front. Mar. Sci. 7 (September), 1–15. https://doi.org/10.3389/fmars.2020.00724.

Villa Castrillón, L., Jacob, B., Badewien, T.H., Staneva, J., 2025. Nature-based solutions: leveraging the coastal protective potential of seagrass in the Jade Bay region. Nat.-Based Solut., 100255 https://doi.org/10.1016/j.nbsj.2025.100255.

Walters, C.J., Holling, C.S., 1990. Large-scale management experiments and learning by doing. Ecology 71 (6), 2060–2068.

Waring, B.G., 2024. Grand challenges in ecosystem restoration. Front. Environ. Sci. 11 (January), 1353829. https://doi.org/10.3389/fenvs.2023.1353829.

Webster, M.S., Colton, M.A., Darling, E.S., Armstrong, J., Pinsky, M.L., Knowlton, N., Schindler, D.E., 2017. Who should pick the winners of climate change? Trends Ecol. Evol. 32 (3), 167–173. https://doi.org/10.1016/j.tree.2016.12.007.

Weible, C.M., Pattison, A., Sabatier, P.A., 2010. Harnessing expert-based information for learning and the sustainable management of complex socio-ecological systems. Environ. Sci. Pol. 13 (6), 522–534. https://doi.org/10.1016/j.envsci.2010.05.005.

Woodroffe, C.D., Murray-Wallace, C.V., 2012. Sea-level rise and coastal change: the past as a guide to the future. Quat. Sci. Rev. 54, 4–11. https://doi.org/10.1016/j.quascirev.2012.05.009.

Xu, K., Chen, J., Feng, Y., Wang, J., Bai, Z., 2023. How are nature-based solutions contributing to the improvement of ecosystem quality in China: A systematic review. Ecol. Indic. 155 (September), 110985. https://doi.org/10.1016/j.ecolind.2023.110985.

Zayonc, D., Coomes, O.T., 2022. Who is the expert? Evaluating local ecological knowledge for assessing wildlife presence in the Peruvian Amazon. Conserv. Sci. Pract. 4 (2), 1–14. https://doi.org/10.1111/csp2.600.

Zhao, Q., Bai, J., Huang, L., Gu, B., Lu, Q., Gao, Z., 2016. A review of methodologies and success indicators for coastal wetland restoration. Ecol. Indic. 60, 442–452. https://doi.org/10.1016/j.ecolind.2015.07.003.