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Exploring marine conservation and climate adaptation synergies and strategies in European seas as an emerging nexus: a review

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Europe's marine and coastal ecosystems provide essential ecosystem services, however, their ability to support climate adaptation and mitigation is increasingly threatened by anthropogenic pressures. This systematic literature review identifies and evaluates integrated approaches that align marine conservation with climate adaptation, revealing untapped potential in leveraging synergies across governance, planning, management, and sectoral integration. Despite extensive research in both fields, their interlinkages remain underexplored, with implementation often fragmented and in early development stages. Our findings identify major nexus approaches, particularly ecosystem-based strategies, which, when effectively applied, strengthen the resilience of coastal social-ecological systems. Central nexus measures include climate-smart marine protected areas, ecosystem restoration (e.g., for wetlands, reefs, dunes, seagrasses), pollution control, and hybrid coastal protection solutions. However, their success hinges on cross-sectoral coordination, robust governance, adaptive management, effective stakeholder engagement, long-term monitoring, and financial sustainability. A critical gap in integrating marine conservation and climate adaptation reflects not only a research shortfall but also barriers in policy and practice. Addressing trade-offs between conservation and adaptation is crucial to maximizing synergies while avoiding unintended socio-economic consequences. The study underscores the need for science-policy integration and transformative governance frameworks to implement nexus strategies at scale. Strengthening regulatory coherence, integrating adaptation into marine spatial planning, and expanding financing mechanisms are critical to operationalizing these measures effectively. These insights provide pathways for policymakers, researchers and practitioners to develop resilient, adaptive marine and coastal management approaches in the face of accelerating climate change.

KEYWORDS

climate change adaptation, marine conservation, coastal resilience, ecosystem services, nexus strategies

1 Introduction

Europe's marine and coastal ecosystems are play an important role in global biodiversity and support environmental and socio-economic stability by providing multifaceted services. These services include climate regulation, the supply of food, renewable energy and cultural value (Abrantes et al., 2019; Day and Rybczyk, 2019; Duarte et al., 2013; EEA, 2019; Fodrie et al., 2017; Gilby et al., 2020). Furthermore, they serve as highly cost-effective natural buffers against climate related threats, protecting coastal communities from sea-level rise, severe flooding, and coastal erosion through, for example, reducing wave attenuation, sediment capture, or storm surge buffering (Narayan et al., 2016; Spalding et al., 2014; Temmerman et al., 2013; van Zelst et al., 2021).

However, their role in climate change adaptation extends beyond coastal protection, delivering diverse ecosystem services, which reduce vulnerabilities to climate impacts including provision of habitat and nursery grounds for marine species (Wedding et al., 2022). Despite occupying a relatively small area, coastal ecosystems are an integral part of the global carbon cycle, capturing and storing about 54 Tg C per year (Wang et al., 2021). They are carbon burial hotspots due to their ability to fix atmospheric carbon dioxide (CO_2) in organic matter through photosynthesis and the capture of carbon-rich sediments in root systems, ultimately leading to long-term carbon sequestration into the soil (Duarte et al., 2005; Howard et al., 2017). In recent decades, the protection of these 'Blue Carbon habitats' has gained increasing attention due to the rise in atmospheric CO_2 concentrations caused by anthropogenic climate change (Macreadie et al., 2017; Serrano et al., 2019).

However, it has become clear that the integrity of marine and coastal ecosystems, their biodiversity, and their capacity for climate mitigation and adaptation is under threat, primarily because of climate change which weakens the resilience of both natural and human systems (Gissi et al., 2021; O'Hara et al., 2021). Strengthening social-ecological resilience involves sustaining processes that maintain biodiversity, promote ecosystem functionality, and support human livelihoods. This fosters adaptive capacity to address both immediate and long-term climate challenges while ensuring the continuity of ecosystem services and human well-being (Lavorel et al., 2020).

Hence, marine conservation and climate adaptation should be integrated through a nexus approach that emphasizes interconnected resources and sectors, fostering cross-sectoral coherence and integration to enhance synergies, minimize conflicts, and address climate change and biodiversity loss effectively. Many studies highlight this need, as traditional approaches often treat them separately, creating a dichotomy (Hoegh-Guldberg et al., 2019; Howard et al., 2023, 2017; Jacquemont et al., 2022; Lovelock and Duarte, 2019; Macreadie et al., 2021; Papadopoulou and Vlachou, 2022; Sumaila et al., 2019; Trebilco et al., 2022). Adopting this approach allows for developing coherent frameworks that simultaneously address ecological, socio-economic, and governance challenges. Such integration ensures alignment between national and regional strategies, local coastal adaptation efforts, and marine management plans, resulting in more robust and adaptive environmental strategies.

Recognizing the importance of healthy and resilient ecosystems in managing climate-related risks has led to the rise of Nature-based Solutions (NbS). Defined by the United Nations Environmental Assembly (UNEA) and aligned with the IUCN Global Standard, NbS provide multifunctional approaches to addressing societal and environmental challenges while benefiting biodiversity (IUCN, 2020; UNEP, 2022). As an umbrella framework, NbS encompass strategies such as Ecosystem-based Adaptation (EbA), Ecosystem-based Disaster Risk Reduction (Eco-DRR), and Ecosystem-based Mitigation (EbM). While all aim to protect, restore, and sustainably manage ecosystems to address climate change, biodiversity loss, and other challenges, EbA stands out by uniquely embodying the nexus approach. It incorporates diverse climate adaptation outcomes, enhances resilience through sector integration, and delivers tailored, localized solutions that effectively bridge climate and conservation priorities (Donatti et al., 2020). While NbS have been widely applied in terrestrial, particularly urban areas, their application in marine and coastal areas remains limited (O'Leary et al., 2023). However, there is growing recognition of their potential in the marine realm through interventions that sustainably manage, restore, and enhance ecosystems, as well as the integration of natural processes into infrastructure design and function (Riisager-Simonsen et al., 2022).

Ecosystem-Based Management (EBM) shares similar goals to NbS by promoting ecosystem health to deliver multiple benefits, including climate adaptation and biodiversity conservation (Delacámara et al., 2020). A key objective of EBM is leveraging policy synergies to balance diverse uses – such as fisheries, tourism, and energy development – while safeguarding ecosystem functionality and resilience to climate impacts. Its emphasis on multi-objective management addresses broader system dependencies, mitigating the risks of sector-specific strategies that can lead to conflicting outcomes (Delacámara et al., 2020).

In Europe, there is a growing emphasis on implementing ecosystem-based approaches, including NbS, EbA and EBM, within coastal, marine, and climate adaptation governance. This shift underscores the importance of "working with nature" by conserving and restoring ecosystems as integral strategies for addressing climatic challenges (Duarte et al., 2013; Hale et al., 2009; Serrano et al., 2019). It is regulated in key EU policies and directives, including the Nature Directives, the Marine Strategy Framework Directive (MSFD), the Common Fisheries Policy (CFP), the Marine Spatial Planning Directive (MSPD), and the recently adopted Nature Restoration Regulation (NRR), along with strategies like the EU Biodiversity Strategy for 2030 and the EU Adaptation Strategy. At the regional level, agreements like OSPAR and HELCOM facilitate cooperation, adding governance layers for managing environmental challenges across sea basins. However, despite these comprehensive laws and frameworks, integration between biodiversity conservation and climate adaptation often remains fragmented and inconsistent (Paramana et al., 2023). Fragmented legal obligations, varying scopes, and misaligned timeframes at the European level lead to conflicting objectives and limited synergies, resulting in disjointed strategies that fail to fully address interconnected challenges (Kyrönviita et al., 2024). At the national level, marine conservation strategies in adaptation plans frequently operate in silos, overlooking effects across sectors (Fuldauer et al., 2022). This fragmentation and lack of cross-sectoral coordination undermines efforts to address interconnected challenges and limits the effectiveness of marine protection and climate adaptation. Strengthening collaboration, aligning policies across governance levels, and fostering integrative planning are essential to bridging these gaps.

This review synthesizes key insights from peer-reviewed publications to highlight nexus strategies and measures of marine conservation and climate adaptation in European seas and coastal areas. It is part of the German federal environment Agency (UBA) funded project MEER: STARK that seeks to foster a cross-sectoral dialogue on this approach at the at European level. By examining contemporary approaches to addressing interconnected conservation and adaptation challenges, the study underscores the added value of integrating these efforts through science-based solutions. Prioritizing implementation-oriented research, the review showcases practical tools, methods, and policymaking applications, offering insights from the European experience to support the development and implementation of effective marine/coastal conservation and adaptation strategies. Through this, the study contributes to advancing transformative science-policy integration for resilient and sustainable coastal management.

We identify, extract, and evaluate nexus strategies from existing studies and asked the following research questions:

1. How is the nexus between marine conservation and climate adaptation presented in the literature?
2. What overarching synergies exist between marine conservation efforts and climate adaptation?
3. Which nexus measures exist and enhance both fields (marine conservation and climate adaptation) and what benefits do they offer?

This review provides a resource for policymakers, environmental managers, and researchers, offering insights into the nexus between marine protection and climate adaptation with a focus on European coasts. The findings offer actionable guidance to enhance nexus strategies, close implementation gaps, foster coordinated governance, and integrate climate-smart approaches for long-term resilience.

2 Methods

2.1 Systematic literature search

A systematic literature review was conducted to identify studies that investigate the nexus between marine and coastal conservation and climate adaptation, excluding those focused solely on climate mitigation. To identify relevant studies, we performed a comprehensive literature search on the database Scopus in March 2023, focusing on studies that were published from 2013 onwards. A second literature query was performed in February 2024, restricting the search to studies published in 2023 and later to update our literature collection with most recently published studies. In both queries, the following search string was used. It combines relevant keywords from the fields of marine conservation, biodiversity, and climate adaptation:

(TITLE-ABS-KEY (marine OR maritime OR coast* OR sea OR seas OR ocean* OR estuar* OR transitional OR lagoon* OR beach*) AND TITLE-ABS-KEY (biodiversity OR ecosystem* OR habitat) OR TITLE-ABS-KEY (biological AND diversity) AND TITLE-ABS-KEY (Climat* AND adaptat*) AND TITLE-ABS-KEY (manag* OR polic* OR measure) AND TITLE-ABS-KEY (europe OR baltic OR "north sea" OR atlantic OR mediterranean OR "black sea")

Of all matches, authors, title, year of publication, keywords, abstract, and the digital object identifier were extracted and screened in a two-step process. In the first screening step, the titles, keywords, and abstracts were reviewed to extract relevant literature for our study. The inclusion criteria were: (i) the nexus between marine conservation and climate adaptation is addressed; (ii) the study is focused on temperate shelf sea regions; and (ii) it was published in 2013 or later. In addition, we screened the studies for implementation-orientation, which describes (a) research that contains tools and methods to support policy making; (b) findings that can be applied in practical future planning; or (c) transformative and science policy research. In the second screening step, the full articles were reviewed for eligibility based on the inclusion criteria. Furthermore, a quality check of the study results was undertaken by mutual cross-checking of the assessments between the authors who performed the literature search to avoid biases.

2.2 Data extraction, analysis, and synthesis

From the selected studies, the following information was extracted: type of study (e.g., review, scientific study), geographic focus area, implementation-orientation, and contribution to both nexus fields. Furthermore, we extracted information on measures (such as nature restoration, management strategies, construction, etc.) that address the joint approach of marine conservation and climate adaptation, the sectors concerned, and the limitations of the measures and/or the study. We then conducted a narrative synthesis of the findings. First, we present the nexus approaches identified by reviewing the selected literature. Nexus approaches refer to strategies and areas that consider marine conservation and climate adaptation together. Examples include respective policy and governance and ecosystem-based strategies. Secondly, we categorize the measures presented in each publication that involve concrete actions aimed at addressing linked nexus challenges.

3 Results

3.1 Literature search

From 305 total matches in the initial literature search, 61 studies passed our selection process. Most studies not selected were dismissed for more than one reason, e.g., not including ecosystems at the European coast and not mentioning the nexus appropriately. Out of the final 61 studies, 51% were published in the first half of our research time frame (2013-2018), and 49% in the second half (2019-2023).

The publications were grouped by focus regions (Figure 1). Seventeen publications focus on the Mediterranean, followed by those adopting a pan-European perspective encompassing multiple sea basins (14 publications). Twelve publications addressed on the global ocean and seven the Atlantic Ocean. Publications categorized as global include assessments of oceanic regions around the U.S. coast, Asian coasts, or Oceania, in addition to sites on the European coast. Six publications investigate Baltic Sea ecosystems, and five publications focus on the North Sea.

3.2 Presentation of the nexus

Expert judgement was used to screen each publication and to extract the nexus approach between marine conservation and climate adaptation. Figure 2 summarizes these nexus strategies, which encompass administrative frameworks ("risk assessment and adaptive management", "policy and governance mechanisms", "integrated management and planning"), implementation strategies ("ecosystem-based approaches", "socio-economic integration"), and balancing competing priorities ("Addressing trade-offs and conflicts and promoting synergies"). Each category has key components that emerged through the synthesis, mapping the nexus. Table 1 presents case study examples illustrating different nexus applications from the core studies, while Supplementary Table S1 provides a detailed breakdown of the strategies, key components, and associated studies.

3.2.1 Ecosystem-based approaches

Ecosystem-based approaches in coastal and marine ecosystems leverage natural processes and ecosystem functions to address climate change adaptation and marine conservation. These approaches are particularly effective in addressing the complex challenges posed by climate change and biodiversity loss, as they consider the interactions between ecosystems, human activities, and environmental stressors. According to Johnson et al. (2018), such approaches integrate ecosystem science, climate adaptation, and precautionary management to enhance sustainability and resilience. Out of the 61 analyzed studies, 16 specifically highlight ecosystem-based approaches that prioritize maintaining ecosystem functions and services as core elements of climate adaptation and marine protection. The identified approaches include Ecosystem-Based Management (EBM), Nature-Based Solutions (NbS), Ecosystem-Based Adaptation (EbA), Conservation of coastal and marine ecosystems (focused on biodiversity protection and ecosystem restoration), and Managed Realignment.

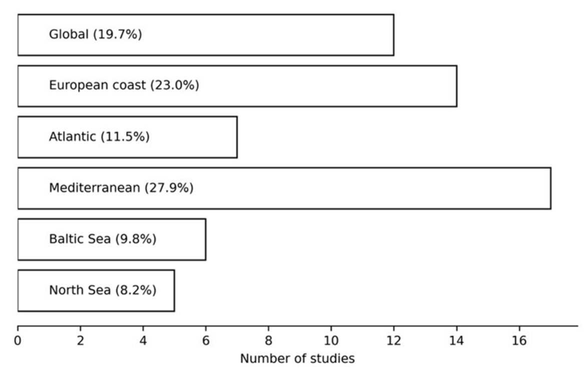

FIGURE 1
Focus regions of the publications. "Global" includes coasts and oceanic regions apart from the European coast. If a study was counted to the category "European coast", the research was conducted either at the entire European coast, or at two or more places along the European coast in different oceanic regions.

EBM emphasizes the interconnectedness of species, habitats, and human activities, aiming to sustain healthy, productive, and resilient ecosystems capable of providing essential services. By considering cumulative impacts and promoting adaptive management, EBM offers a dynamic approach to addressing changing environmental conditions, including those driven by climate change. While none of the reviewed studies explicitly mention EBM, its principles align inherently with the nexus framework. As a foundational concept for integrated management, EBM supports synergies between marine conservation and climate adaptation strategies. Its relevance is reflected in many approaches discussed in this review, including EbA, restoration efforts, and risk assessment and adaptive management. By fostering a holistic perspective, EBM addresses the interconnected challenges of biodiversity loss, climate change, and sustainable resource use, making it a critical enabler of other ecosystem-based approaches.

NbS encompass interventions leveraging the functions of natural habitats to mitigate climate impacts and boost ecological and community resilience. We identify NbS as an ecosystem-based nexus strategy. EbA can be considered a subset of NbS focusing specifically on using biodiversity and ecosystem services as adaptation strategies coping with climate change. While NbS include a broad range of nature-based interventions, EbA emphasizes adaptation as a primary goal. Many NbS initiatives incorporate adaptation objectives, making EbA integral to NbS strategies. In coastal zones, NbS such as depolderization - removing artificial barriers to enable tidal flooding - combine flood protection with habitat regeneration (Goeldner-Gianella et al., 2015). Sustainable harvesting practices, such as those advocated by Ortega et al. (2023), support fisheries sustainability and climate adaptation, while management of macroalgae beds enhances ecosystem resilience, mitigates ocean acidification, and supports stability while delivering economic benefits (Takolander et al., 2017). Muñoz et al. (2023) endorse sustainable fishing and conservation to counteract negative climate change impacts on marine biodiversity and coastal communities.

Conservation of coastal and marine ecosystems, through protection and restoration, enhances biodiversity, reduces vulnerability to climate-related hazards, and supports well-being

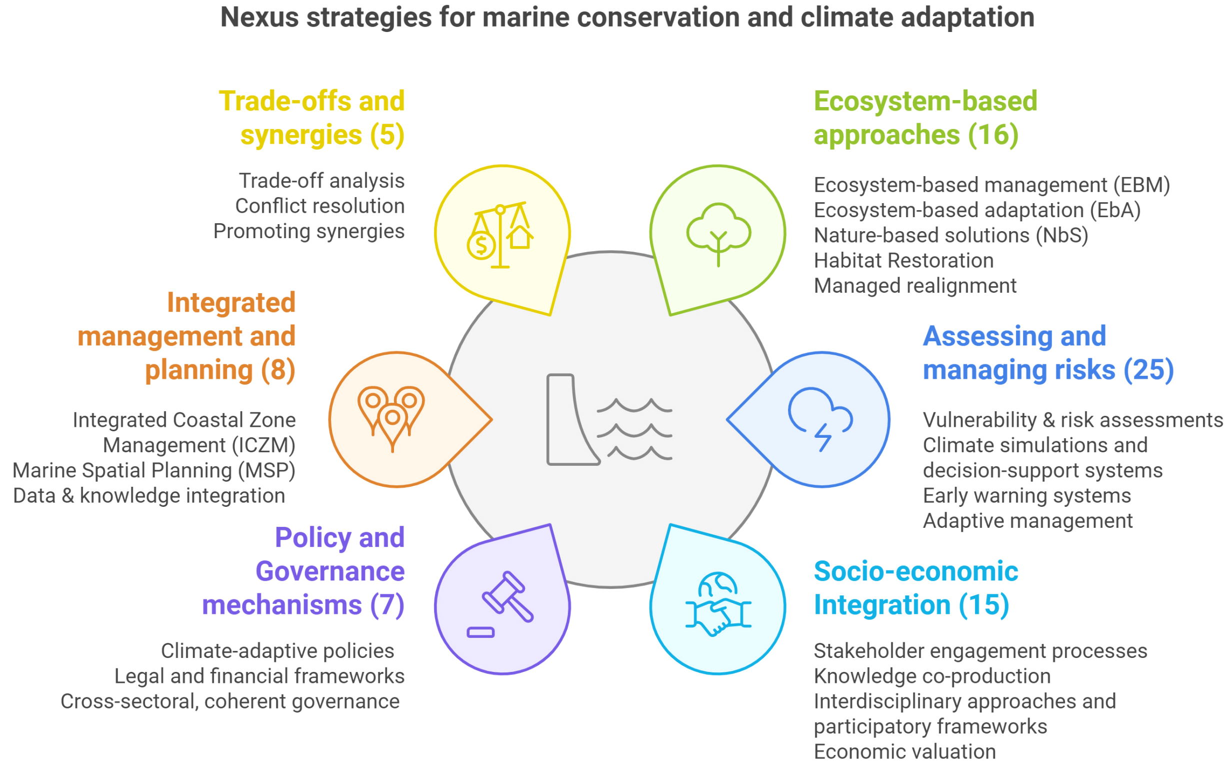

FIGURE 2
Schematic diagram and visual presentation of the literature review results, highlighting the identified nexus approaches. Number of studies are indicated in parentheses. 34 studies address two or more nexus strategies, leading to the total number of studies across strategy categories (76) exceeding the number of unique studies (61).

and livelihoods. Protection approaches, such as the establishment and expansion of marine protected areas (MPAs), are important for both marine conservation and climate adaptation. These efforts focus on minimizing pressures on well-preserved ecosystems, from fully or strictly protected areas to zones with minimal protection. Restoration efforts bolster resilience by rehabilitating degraded ecosystems, ranging from partial to full restoration and even creating novel ecosystems. Both protection and restoration are

TABLE 1 Case study overview of nexus approaches in Europe.

Nexus Approach	Reference	Sea Basin	Case Study	Success factors / Barriers
Nature-based Solutions (NbS) (see 3.2.1)	Ortega et al., 2023	Mediterranean	The paper identifies and prioritizes six potential priority areas for management in the western Mediterranean Sea.	These areas are specifically aimed at the protection and recovery of Essential Fish Habitats and the conservation of Vulnerable Marine Ecosystems, whilst requiring limited adaptation of fisheries practices due to their relative low fishing pressure.
Adaptive management (see 3.2.2)	Derolez et al., 2023	Mediterranean	Coastal social-ecological systems require adaptive management based on integrated interdisciplinary approaches, to be resilient. The authors developed a method to analyze co-evolution and regime shifts, and it was tested in a case study in France.	Approach based on long-term trajectories will help identify the conditions required for increasing the resilience of coastal Social-ecological system and the best management objectives to face new challenges related to global climate change.
Stakeholder engagement processes and knowledge co-production (see 3.2.3)	West et al., 2021	European Seas	Presenting five different regional coastal cases from the CoCliME Projec, which focused on the co-development of approached to address Harmful Algal Blooms using a transdisciplinary approach.	Developed mechanisms to facilitate inter- and transdisciplinary communication, like a shared terminology among stakeholders. The paper highlights the importance of understanding stakeholders multi-risk decision-making contexts and information needs.
Integrated management of coastal zones (see 3.2.5.)	Karrasch et al., 2014	North Sea	The case study focuses on integrated coastal land use management and proposes a planning approach that links the ecosystem services approach to social preferences and needs.	Integrating local stakeholders, using a planning approach integrating the ecosystem services approach and social impact analysis

often integral to NbS and EbA strategies, but they also stand alone as critical components of the nexus approach. Integrating these efforts into broader adaptation frameworks ensures a comprehensive response to climate change challenges, essential for building sustainable and resilient coastal environments. For instance, the conservation of salt marshes and seagrass meadows supports their role in absorbing storm surges, stabilizing and filtering coastal sediments and pollutants preserving coastal water quality and supporting marine life, reducing erosion, and enhancing shoreline protection, thereby mitigating the effects of sea-level rise while also sequestering carbon (Balestri et al., 2017; Filho et al., 2022; Hofstede, 2019). Ondiviela et al. (2014) highlight the potential of seagrass meadows for coastal protection and suggest adaptation measures to counter their decline. Coastal dunes enhance climate resilience by acting as barriers against extreme weather and supporting diverse plant and animal communities. Laporte-Fauret et al. (2021) emphasize the importance of integrating ecosystem health, climate resilience, habitat restoration, and sustainable management to maintaining the dunes' protective and ecological functions. Two studies suggest that existing NbS approaches should be "layered up", for example by conducting active restoration within MPAs, testing new strategies that combine short- and long-term interventions, as well as restoring multiple habitats simultaneously and across the land-sea interface for synergistic effects (O'Leary et al., 2023; Sánchez-Arcilla et al., 2016). This comprehensive approach promotes structural and functional connectivity, addressing immediate climate-related threats while promoting long-term sustainability under higher emission scenarios.

Managed realignment, or managed retreat, is an increasingly critical component of national and regional climate adaptation strategies, particularly in coastal areas vulnerable to sea-level rise and extreme weather events. As an ecosystem-based strategy, it offers multi-benefit solutions by supporting biodiversity, enhancing ecological resilience, and promoting sustainable coastal management. Managed realignment involves the deliberate landward relocation of coastal defenses to restore natural habitats like salt marshes. By allowing tidal flooding through the removal, breaching, or setting back of embankments, these measures not only reduce flood risks but also enable wetland regeneration, providing essential ecosystem services (Schernewski et al., 2023; Schuerch et al., 2022). Additionally, restored habitats contribute to biodiversity, recreational opportunities, and carbon sequestration. Biodiversity benefits are achieved by allowing natural processes to restore ecosystems and mitigate further habitat loss due to coastal squeezing, creating critical habitats for various species. For instance, removing dams and improving fish passages enhances aquatic ecosystem resilience by enabling species movement (Thorstad et al., 2021). Esteves (2013) highlights the need to balance ecological, socio-economic, and practical considerations, particularly when implementing large-scale projects that may require the relocation of communities or agricultural activities. Similarly, Hofstede (2019) highlights the importance of local community acceptance. Schuerch et al. (2022) stress the need for local community acceptance, addressing land-use concerns, and overcoming perceptions of limited effectiveness compared to traditional engineering techniques. While upfront and maintenance costs, as well as uncertainties in ecological outcomes under varying climatic scenarios, present challenges, adaptive governance, stable funding, and strong stakeholder engagement can ensure its long-term success. Hofstede (2019) underscores the viability of managed realignment as an effective nexus solution, particularly in vulnerable areas like the Wadden Sea, where it integrates marine conservation with climate adaptation to reduce coastal risks and foster ecosystem resilience.

In summary, ecosystem-based approaches, including EBM, NbS and EbA, utilize natural processes to provide significant benefits for marine conservation and climate adaptation. Restoring and sustainably managing habitats enhances ecosystem resilience, protects biodiversity, and addresses climate hazards, delivering multifaceted benefits for both the environment and human societies.

3.2.2 Risk assessment and adaptive management

Twenty-five studies highlight risk assessment and adaptive management as essential nexus strategies for developing long-term strategies to sustain ecosystem functions and structures. Understanding climate change impacts on marine ecosystems informs conservation and adaptation efforts, while climate risk assessment and adaptive practices support social-ecological resilience. Emphasizing flexibility and responsiveness, these strategies enable effective management under uncertain and changing conditions.

Vulnerability and risk assessments play a crucial role in identifying the susceptibility of ecosystems, species, and coastal communities to climate-related stresses, enabling the prioritization of adaptation actions. Assessing species vulnerabilities informs adaptation strategies and identifies species or habitats most at risk, allowing for targeted management actions and effective adaptation strategies (Payne et al., 2021). Poumadère et al. (2015) stress the need for proactive risk management strategies to address the increasing vulnerability of coastal environments to erosion and submersion due to sea level rise. Barange et al. (2016) emphasize interdisciplinary collaboration and risk management strategies. Several studies highlight the importance of regional risk assessment models. Rizzi et al. (2016) develop a Regional Risk Assessment methodology to inform decision-making and adaptation strategies in shoreline planning and flood risk reduction. Payne et al. (2021) present a framework for assessing climate risks faced by ocean-dependent communities including fishing fleets, which considers geographical differences in climate hazards and regional variability. Harrison et al. (2015) propose integrated models for cross-sectoral impacts and non-climatic pressures to capture the effects of climate change on a regional scale. Hofstede and Stock (2018) stress maintaining the integrity of the Wadden Sea ecosystem, calling for ecosystem-based strategies for coastal risk management. The assessment of vulnerable coastal fisheries and fishing communities provides valuable information for adaptation planning (Pinto et al., 2023).

Climate simulations and decision-support systems are proposed by several studies to guide strategic adaptation planning. Barredo et al. (2016) assess habitat losses and improve conservation actions, highlighting the importance of understanding the impacts of climate change. Rizzi et al. (2016) address the impacts of climate change on marine ecosystems using climate change scenarios with site-specific environmental and socio-economic indicators. Flood probability maps evaluate the joint impacts of flooding and socio-economic development on future ecosystem services (Magalhães Filho et al., 2022). Colombano et al. (2021) present a multiple stressor framework to quantify the short- and long-term impacts of climate change on tidal marsh ecosystems. Torresan et al. (2016) use a GIS-based decision support system to analyze climate change risks and impacts to human assets and ecosystems to support strategic adaptation planning. Inundation risk mapping (Rizzo et al., 2022) aids decision-making by visualizing potential scenarios under different sea-level rise projections. Jueterbock et al. (2018) discuss the climatic vulnerability of marine species, calling for adaptive management strategies in marine conservation efforts. Estrela-Segrelles et al. (2021) utilize a comprehensive assessment methodology to identify impacts on hydrology, ecology, and socio-economic systems, recommend adaptation measures, and provide insights into transferability. By considering the multi-dimensional nature of sea-level rise impacts on coastal wetlands, the study aims to inform adaptive management and conservation strategies to mitigate the adverse effects of environmental change. Hoggart et al. (2014) offer a comprehensive review of ecological and socio-economic impacts of seawater flooding, underscoring the inclusion of diverse coastal ecosystems, experimental and modelling approaches, and emphasize climate change considerations. The study provides a holistic understanding of the implications of seawater flooding on coastal ecosystems and communities.

Early warning systems monitor environmental changes and provide timely information to support decision-making. The tools enhance the capacity to respond effectively to climate change impacts by enabling proactive management actions. West et al. (2021) discuss the development of early warning systems to support stakeholders' decision-making in managing climate risks to marine ecosystems. The early engagement of stakeholders and co-development increases the quality of knowledge for management. Integrating early warning systems with adaptive management frameworks allows for real-time responses to environmental changes (Sánchez-Arcilla et al., 2016) and facilitates short- and long-term interventions with complementary objectives, achieving synergistic effects in building resilience.

Adaptive management is essential for ensuring the effectiveness of marine conservation and climate adaptation efforts amid accelerating climate change impacts. By systematically improving policies and practices through learning from implemented strategies, adaptive management allows for flexibility and responsiveness to changing environmental conditions. Goeldner-Gianella et al. (2015) highlight the vulnerability of marine biodiversity to the combined effects of climate change and overfishing, emphasizing the necessity of adaptive management strategies to respond to dynamic impacts and mitigate cumulative pressures. Merino et al. (2019) reinforce the need for flexible management frameworks that can adjust to new information, pointing to uncertainties surrounding the best course of action to mitigate against the evolving threats from climate change on marine ecosystems and fisheries. Similarly, Howard and Pecl (2019) stress the interconnectedness of biodiversity changes, human adaptation, and climate impacts on marine ecosystems. They advocate for interdisciplinary collaboration to develop flexible management strategies that can accommodate shifting species distributions and ecosystem dynamics. Vogiatzakis et al. (2016) and Barredo et al. (2016) address this in the context of Mediterranean islands, where biodiversity is highly vulnerable to climate stressors. They note that buffer zones, dispersal corridors, and habitat networks play an essential role in maintaining landscape connectivity and supporting biodiversity conservation under changing climate conditions. Incorporating these elements into adaptive management plans enhances the responsiveness and effectiveness of conservation efforts in combating the climate crisis. Barange et al. (2016) discuss the dynamic nature of environmental changes and advocate for the widespread adoption of adaptive management and precautionary principles. Derolez et al. (2023) exemplify this approach by employing an interdisciplinary framework that combines historical data analysis with stakeholder engagement to identify key drivers of change and resilience in coastal areas. Their methodology emphasizes the importance of adaptive management and resilience-building strategies in the face of environmental uncertainties.

Incorporating climate considerations into spatial planning and management is crucial for effective conservation and adaptation strategies. Marine Spatial Planning (MSP) is a foundational tool in integrated management, guiding the timing and location of human activities in marine spaces to reduce conflicts and facilitate compatible uses. From a nexus perspective, it has the potential to ensure that conservation and adaptation goals are sustainably achieved. To be effective under changing conditions, MSP should become increasingly climate-smart by integrating climate impacts – such as species range shifts and climate velocity – into spatial allocations (Queirós et al., 2021). Similarly, designing climate-smart Marine Protected Areas (MPAs) involves identifying and effectively protecting climate refugia and biodiversity hotspots to withstand climate impacts and accommodate future shifts in species distributions (Arafeh-Dalmau et al., 2021). By aligning climate-smart MSP and MPAs, planners can develop adaptive strategies that enhance ecosystem resilience, address cumulative pressures, and support both conservation and sustainable use of marine resources.

In synthesis, creating multifunctional landscapes supporting response diversity – the ability of ecosystems to respond to environmental changes in different ways – is key for the successful adaptation of coastal areas. Such landscapes enhance resilience to sea-level rise and other climate impacts by incorporating ecosystem functions through adaptive management (Schibalski et al., 2022).

3.2.3 Socio-economic integration

Our analysis identified 15 studies highlighting socio-economic integration as a key nexus approach, emphasizing the inclusion of social, economic, and cultural factors in protection and restoration strategies. This approach fosters stakeholder engagement, interdisciplinary collaboration, and the integration of traditional and scientific knowledge to manage climate risks. Socio-economic integration ensures socially acceptable, economically viable solutions that enhance resilience through ecological and social adaptation, including integrated coastal land use management to address climate change impacts on marine ecosystems.

Stakeholder engagement processes and knowledge co-production are essential for addressing climate risks in marine ecosystems. Several studies stress the significance of involving stakeholders and fostering transdisciplinary processes (Mokrech et al., 2016; West et al., 2021). Early stakeholder engagement, exchange on common challenge and co-developing solutions improve the quality of knowledge for managing climate risks such as harmful algal blooms (West et al., 2021). This collaborative approach improves the relevance and usability of scientific knowledge for decision-making, ensuring that strategies are tailored to local contexts and needs. Ahlvik and Hyytiäinen (2015) stress collaborative decision-making and adaptive management, ensuring flexibility and responsiveness to environmental changes and societal needs. Mokrech et al. (2016) illustrate this approach with participatory modelling, exploring socio-economic scenarios, and co-creating adaptation strategies for flood risks in European coastal areas. Moraes et al. (2022) note that sharing knowledge on issues and solutions with the broader public and stakeholders help avoid previous mistakes and facilitate the replication and implementation of NbS.

Interdisciplinary approaches integrating social, economic, and cultural aspects are essential for effective ecosystem-based adaptation strategies (Bertolini and da Mosto, 2021; Estrela-Segrelles et al., 2021). Combining local and scientific knowledge enables successful responses to climate challenges in coastal and marine planning, including MPAs (Fatorić and Morén-Alegret, 2013).

Participatory frameworks, like living labs, co-develop, test and scale ecosystem-based strategies aimed at addressing complex and interconnected challenges, often referred to as "wicked problems" (Tiwari et al., 2022). These frameworks integrate local knowledge with scientific insights, and adaptable, holistic solutions in climate-affected coastal regions, ensuring that strategies are scientifically sound and socially inclusive, enhancing their long-term sustainability.

Participatory vulnerability analysis, encompassing social, cultural, environmental, economic, and political dimensions, informs adaptation strategies and enhances resilience in regions facing significant challenges, such as the Mediterranean, which is highly vulnerable to climate change impacts and socio-economic pressures (Fatorić and Morén-Alegret, 2013). Integrating environmental projections with socio-economic indicators, like income levels, employment in climate-sensitive sectors, and access to resources, alongside exposure, sensitivity, and adaptive capacity, allows vulnerability assessments to deliver targeted adaptation planning (Mokrech et al., 2016; Pinto et al., 2023). By simulating the impacts of sea-level rise and extreme events and assessing potential land-use changes and economic implications, decision-makers can prioritize adaptation strategies that maximize socio-economic benefits while protecting coastal-marine ecosystems (Hérivaux et al., 2018). Understanding the vulnerabilities of coastal wetlands, and recommending socio-economic adaptation measures, enhances resilience of coastal communities (Estrela-Segrelles et al., 2021). Hyytiäinen et al. (2019) integrate socio-economic and climate drivers with biogeochemical and ecosystem models to project future trajectories and explore policy and management implications for addressing climate change impacts on the Baltic Sea. By quantifying ecosystem dynamics and assessing potential changes under various scenarios, the study provides valuable insights into trade-offs and opportunities associated with different strategies. Harrison et al. (2015) emphasize the need to account for socio-economic changes when assessing flood risk and developing decision support tools. Similarly, Derolez et al. (2023) propose an innovative analytical framework for examining the long-term trajectory of coastal social-ecological systems, highlighting the importance of incorporating stakeholder perspectives into adaptation strategies.

Economic valuation and economic support mechanisms are intended to garner public and policy support for conservation projects. Assigning economic value to benefits like flood protection, habitat conservation, and carbon sequestration facilitates the implementation of restoration initiatives (Bertolini and da Mosto, 2021; Estrela-Segrelles et al., 2021). This economic framing justifies the allocation of resources towards these projects and highlights their cost-effectiveness. An example are natural barriers like restored wetlands that can provide flood protection at much lower costs compared to man-made infrastructure, whilst offering ecological benefits and fostering resilience. Economic support mechanisms also facilitate social adaptation by enabling the diversification of livelihoods and encouraging investments in sustainable practices. Restored ecosystems can create new opportunities for eco-tourism, sustainable fisheries, and other green industries, providing alternative income sources for coastal communities (Thorstad et al., 2021; Woods et al., 2022).

3.2.4 Policy and governance mechanisms

Seven studies highlight policy and governance mechanisms that support nexus integration through cohesive policies, legal frameworks, and institutional arrangements. Effective governance ensures coordinated actions across sectors and scales, making conservation and adaptation efforts enforceable, adequately financed, and aligned with stakeholder needs.

Climate-adaptive policies account for the impacts of climate change on marine ecosystems and incorporate adaptive management principles, ensuring effective conservation efforts. Cheung et al. (2018) stress the need for climate-adaptive fisheries management and conservation plans in international waters. Fisheries restricted areas are a potential NbS-measure for upscaling sustainable fisheries and climate adaptation (Ortega et al., 2023). Aurelle et al. (2022) explore the role of MPAs in conservation and population adaptation, acknowledging the challenges faced in the context of climate change. Graversen et al. (2022) address the nexus between climate adaptation and marine protection by quantifying carbon sequestration in salt marshes, emphasizing blue carbon management strategies.

Strengthening legal and financial frameworks through robust governance arrangements and well-designed policy instruments, provide the necessary foundation for implementing effective management and conservation measures, such as the designation and effective management of MPAs. These frameworks play a vital role in securing sustainable financing and addressing local community concerns, to ensure enforceable conservation efforts aligned with stakeholder needs (López-Dóriga et al., 2020).

Establishing cross-sectoral and coherent governance structures is crucial for facilitating coordination in marine conservation and climate adaptation to enable the integration of diverse perspectives and expertise, enhancing the effectiveness of measures. Thorstad et al. (2021) underscore the understanding of human dimensions, engaging communities, and addressing governance issues in conservation efforts to promote the resilience of marine ecosystems. Payne et al. (2021) address effective adaptation strategies for ocean-dependent communities facing climate change impacts, through establishing effective governance frameworks.

3.2.5 Integrated management and planning

Eight studies highlight an integrated nexus approach that recognizes the interconnectedness of marine ecosystems, conservation, and climate change responses. This approach synthesizes multidisciplinary knowledge, incorporates stakeholder perspectives, and develops proactive strategies to enhance coastal resilience and sustainability. By integrating ecological, social, and economic factors, holistic management and planning facilitate coordinated, synergistic actions across sectors, embedding nature conservation and climate adaptation into decision-making processes.

Integrated management of coastal zones, including Integrated Coastal Zone Management (ICZM), is a holistic and adaptive process that fosters sustainable coastal management by aligning stakeholder interests and integrating insights from terrestrial and marine environments with the aim to balance environmental, economic, social, cultural, and recreational objectives in an integrated manner. By considering sustainable management practices across the marine-freshwater interface, ICZM addresses the challenges posed by climate change and supports marine conservation efforts ensuring that coastal conservation and development efforts are coordinated and mutually supportive. Karrasch et al. (2014) demonstrate how integrated coastal land-use management approaches enhance resilience in coastal areas by linking ecosystem services to social preferences and needs. Seiffert and Hesser (2014) demonstrate how ICZM incorporates scientific knowledge and hydrodynamic modelling into management strategies, to predict climate impacts and develop more effective adaptation strategies. It emphasizes the need to recognize complex interactions within coastal ecosystems and adapt to climate change impacts, particularly in estuarine habitats where proactive conservation can bolster ecosystem resilience. Berry et al. (2015) advocate for cross-sectoral planning within ICZM, integrating fisheries, tourism and conservation sectors to ensure coordinated actions for multiple objectives. By aligning sectoral goals, ICZM enhances the effectiveness of both marine conservation and climate adaptation efforts, promoting a balanced approach that benefits various stakeholders.

MSP plays a crucial role in integrating ecological and socio-economic factors into regional coastal climate adaptation. Schernewski et al. (2023) highlight how MSP can identify areas where conservation and adaptation efforts are most effective. Multiple stressor frameworks and multi-hazard assessments pinpoint ecosystem vulnerabilities, guiding targeted spatial planning. Studies by Hérivaux et al. (2018); Torres et al. (2021), and Magalhães Filho et al. (2022) show how MSP integrates climate resilience into coastal protection to mitigate risks like sea-level rise and coastal flooding. By incorporating climate projections MSP guides the allocation of space for conservation areas, infrastructure development, and adaptation measures, ensuring that marine and coastal environments are managed proactively for resilience. Torres et al. (2021) showcase an integrated approach using expert opinion and socio-economic considerations to recommend tailored adaptation actions enhancing resilience in tourism-dependent coastal communities, demonstrating the role of MSP in stakeholder engagement and planning.

Data integration and knowledge sharing are essential for effective integrated management and planning allowing strategies to reflect marine and coastal complexity, anticipate future changes, and implement adaptable measures based on robust data and transdisciplinary knowledge. Meiner (2013) underscores data integration and comprehensive assessment for adaptive strategies, including multi-dimensional mapping of parameters like seafloor topography, sediment composition and biodiversity distribution, allowing for a nuanced understanding of ecosystem dynamics. Enhanced data sharing, standardization, and integration of spatial data, socio-economic drivers, and associated pressures are critical for informed decision-making.

3.2.6 Addressing trade-offs, conflicts and promoting synergies

Five studies explore strategies to manage trade-offs, resolve conflicts, and harness synergies for balanced and effective outcomes. Addressing conflicts and managing trade-offs between conservation and adaptation is critical to maximizing synergies and minimizing negative impacts. Trade-off analyses and conflict resolution mechanisms enable decisions that balance ecological, social, and economic priorities while mitigating unintended consequences of adaptation strategies.

Trade-off analyses explore the costs, benefits, and impacts of adaptation and conservation strategies, weighing ecological, economic, and social priorities. They help identify potential conflicts, such as between immediate needs of coastal communities and long-term ecosystem resilience, informing integrated decision-making. For example, while reducing greenhouse gas emissions is critical for mitigating climate change, certain measures may not address urgent threats to marine ecosystems, requiring complementary adaptation strategies. Managed realignment should enhance biodiversity and carbon sequestration but may require sacrificing habitats, agricultural land, or relocating communities (Esteves, 2013). Soft shoreline protections like seagrass meadows offer ecosystem services supporting adaptation and mitigation but can conflict with fishing and boating and may need recovery time after extreme weather. Similarly, using salt marshes for flood defense can harm their ecological functions and the species they support, as seen along the Wadden Sea coast (van-Loon-Steensma, 2015). In the Doñana wetlands, profit-driven rice production conflicts with sustainable water management needed for coastal ecosystem resilience (Iglesias et al., 2017). Prioritizing and subsidizing new water infrastructure exacerbates water scarcity, threatening long-term sustainability and highlighting the need to favor long-term resource availability over immediate economic gains.

Promoting synergies requires integrated approaches that balance trade-offs and identify overlaps between conservation and adaptation objectives, enhancing the effectiveness of nexus strategies and delivering multiple benefits. Integrating biodiversity into adaptation strategies can enhance coastal protection while preserving ecosystems, demonstrating natural habitats' potential for multiple purposes and synergies. Promoting the sustainable use of seagrass ecosystems through initiatives like ecotourism and sustainable fishing practices can simultaneously support conservation goals, enhance local livelihoods, and strengthen ecosystem resilience. Across the identified approaches, there is a clear need to prioritize "no-regrets" measures – those that deliver benefits regardless of future uncertainties – while continuously refining strategies as scientific understanding and environmental conditions evolve (e.g. Johnson and Holbrook, 2014).

Conflict resolution mechanisms, like participatory decision-making reconcile interests by engaging stakeholders in balancing goals. Schibalski et al. (2022) evaluate trade-offs in coastal zone management strategies aimed at enhancing resilience to climate change. The "hold-the-line" strategy preserves farmland but causes soil salinization, while "managed realignment" sacrifices short- to medium-term farm income by repurposing land for natural processes like tidal flooding. Over the long-term, however, managed realignment boosts ecosystem services such as water retention, carbon sequestration, and biodiversity. The study highlights the need to balance immediate economic impacts with long-term ecological benefits. Engaging farmers in decision-making processes can address income concerns through compensation or alternative livelihoods, fostering collaborative solutions that support both economic viability and ecological resilience.

By thoughtfully balancing priorities and engaging stakeholders, negative impacts can be mitigated and positive outcomes enhanced, ensuring that adaptation and conservation efforts are mutually beneficial.

3.3 Presentation of the measures

The identified nexus strategies are accompanied by a set of measures that offer practical solutions to the interconnected crises of marine biodiversity loss and climate change (Figure 3). Table 2 presents case study examples illustrating different nexus measures from the core studies, while Supplementary Table S1 provides a detailed breakdown of the measures, sub-measures, and associated studies. While some measures may primarily address one challenge more than the other, they are all derived from studies that discuss one or more nexus strategies. Each measure includes multiple sub-measures, with detailed descriptions provided in the subsequent chapters.

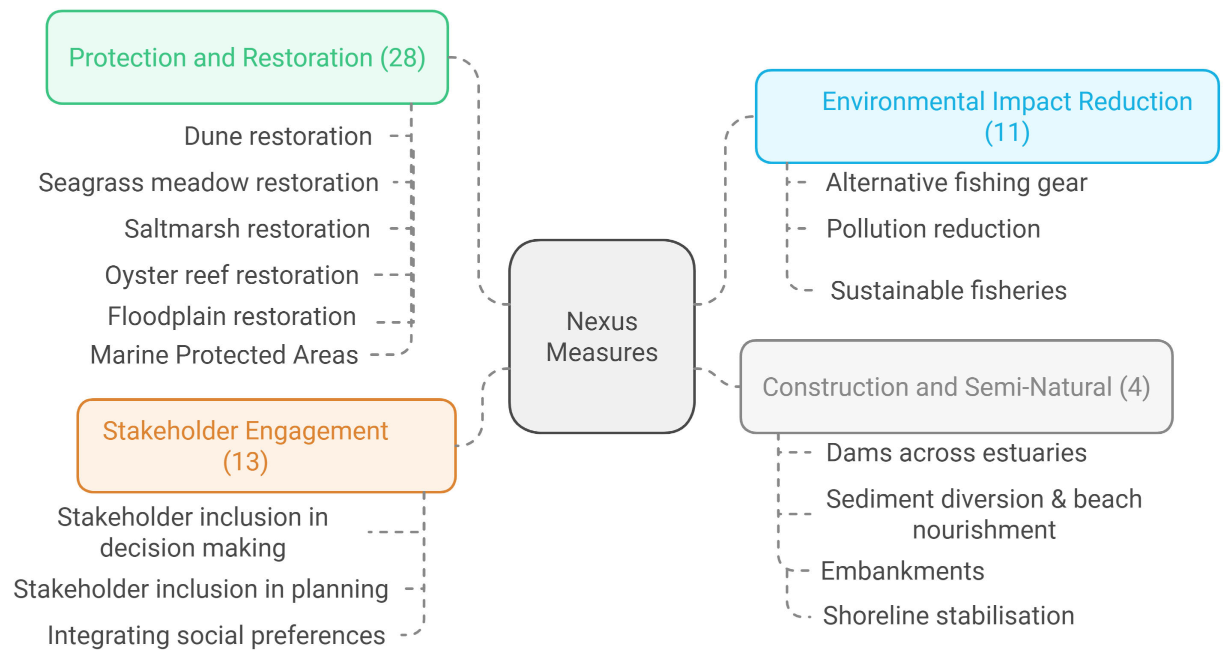

FIGURE 3
Nexus measures in the selected publications. A total of 17 studies address two or more nexus measures, contributing to the total of 56 studies categorized by measures. This total is lower than the 61 unique studies included in the entire review. Additionally, 20 publications were not assigned to any specific measure category, as they discuss the nexus concept without proposing specific implementation methods.

TABLE 2 Case study overview of nexus measures in Europe.

Measures	Reference	Sea Basin	Case Study	Success factors / Barriers
Marine Protected Areas (see 3.3.1)	Arafeh-Dalmau et al., 2021	Mediterranean	The study designs climate-smart MPA networks by incorporating climate velocity. It identifies stable climate refugia using 4,649 planning units and spatial prioritization software to enhance ecological resilience and species movement.	Success stems from a transparent, replicable method applicable to marine and terrestrial systems. It aligns with climate-smart adaptation by prioritizing slow-moving climate areas. A multidisciplinary approach ensures practical relevance, though additional climate impact measures are needed for a comprehensive strategy.
Restoration of dunes (see 3.3.1)	Laporte-Fauret et al., 2021	Atlantic	The study examines the impact of experimental notches on coastal dune morphology and vegetation in Southwest France. Eight notches were excavated and monitored over two years, revealing that sand deposition increased, enhancing plant diversity.	The study demonstrates that notches can enhance sand accretion, support plant regeneration, and restore coastal dunes, making them a potential adaptation strategy for sea level rise and erosion. The findings highlight the role of notches in rejuvenating plant communities and restoring dune ecosystems.
Beach nourishment (see 3.3.3)	Hofstede and Stock, 2018	North Sea	The paper focus on the integrated state governmental strategy for climate change adaptation in the Schleswig-Holstein (Germany) sector of the Wadden Sea with beach nourishment to adjust for the sea level rise	Some lessons learnt are presented in the study, for example the integration of different interests, and the aim to reduce conflict potential beforehand.
Stakeholder inclusion in planning processes (see 3.3.4)	Moraes et al., 2022	European Seas	Paper analyses 59 case studies on NbS for coastal defense in Europe. For example, one case study of shellfish reefs in the Eastern Scheldt described a well-structured stakeholder engagement plan, using diverse communication methods.	One of the lessons learned emphasized stakeholder involvement as essential for effective NbS implementation. Additionally, cases highlighted gaps in biological, ecological, and physical site-specific knowledge as critical barriers when unavailable.

3.3.1 Protection and restoration measures

Different protection and restoration measures for marine and coastal protection and adaptation to climate change were identified in 28 studies. These measures play an important role in addressing challenges posed by climate change, especially in vulnerable coastal areas where impacts are often severe. By restoring and enhancing natural ecosystems, they aim to build resilience against environmental stressors and mitigate climate-related risks effectively.

Marine Protected Areas are essential for conservation and climate adaptation in coastal and marine environments. They safeguard genetic diversity, connectivity, and ecosystem resilience, which underpin long-term ecological and adaptive success. MPAs are long-term ecological conservation areas in the ocean that mitigate and promote adaptation to climate change by protecting ecosystems from damage and degradation (Roberts et al., 2017; Schmidt et al., 2022). Cheung et al. (2018) and Arafeh-Dalmau et al. (2021) discuss the effectiveness of MPAs in safeguarding vulnerable species and habitats, while also acknowledging the need for adaptive fisheries management within these protected zones. They also stress the development of ecosystem-based management approaches and climate smart networks in these areas (Arafeh-Dalmau et al., 2021; Cheung et al., 2018). Aurelle et al. (2022) recommend that MPAs be strategically located based on specific genetic, phenotypic, and habitat diversity, ensuring connectivity among MPAs. This approach enables MPAs to serve as refugia for species and habitats vulnerable to climate impacts and may facilitate spontaneous ecosystem adaptation. Connectivity is crucial for demographic recovery, range shifts, and genetic adaptation through the spread of advantageous alleles and access to refugia. Protecting populations across environmental gradients – such as altitude, depth, and diverse habitats – and from distant regions enhances resilience. Johnson et al. (2018) assess climate change impacts on MPAs in the North Atlantic, highlighting the importance of improving the measurement framework of MPAs to enhance their effectiveness in conservation and adaptation efforts. Furlan et al. (2018) present a screening tool that assesses the environmental status of MPAs, assisting managers in identifying priority zones or areas for improvement within MPAs to enhance conservation and adaptation outcomes and strengthen ecosystem resilience. Jueterbock et al. (2018) underscore the role of genetic diversity in boosting adaptive potential in intertidal seaweed populations over time, implying that habitat conservation efforts should prioritize maintaining diverse population.

Habitat restoration and its role in supporting both ecological resilience and climate adaptation is underscored in several studies. Woods et al. (2022) and López-Dóriga et al. (2020) focus on specific actions, such as coastal wetland creation and dune management, that address immediate coastal challenges while preparing ecosystems for future impacts. Similarly, Thorstad et al. (2021) emphasize that restoring habitats not only corrects past ecological damage but also promotes sustainable ecosystem functioning in the long term. Hoggart et al. (2014) add further depth by exploring how coastal habitat restoration can mitigate specific threats like seawater flooding. These insights collectively highlight that restoration is not just about reversing degradation but also about building adaptive capacity in ecosystems to face future environmental shifts.

Restoration of coastal wetlands holds immense potential in climate adaptation efforts, given these ecosystems serve as natural barriers against coastal erosion and providing crucial habitat for diverse species. Bertolini and da Mosto (2021) underscore the multifaceted role of coastal wetland restoration in climate adaptation, emphasizing its contribution to biodiversity conservation and its effectiveness in mitigating climate-related impacts. Additionally, Hoggart et al. (2014) highlight the effectiveness of coastal wetland restoration as NbS to mitigate the impacts of seawater flooding. Schernewski et al. (2023) further increase the understanding of the importance of wetland restoration in coastal climate adaptation planning. Their study reflects on the integration of spatial and sectoral planning approaches to address regional climate change, particularly sea-level rise. By analyzing ecosystem service assessments, the study outlines the potential of wetland restoration as a key component of regional coastal climate change adaptation strategies. Restoration of floodplains, discussed by Mokrech et al. (2016) and Berry et al. (2015), serves as an essential adaptation option for mitigating flood risks and enhancing ecological resilience. This measure not only aids in flood management but also contributes to habitat restoration.

Restoration of saltmarshes has gained attention as these are critical ecosystems for coastal resilience against sea-level rise and flooding. As highlighted by van-Loon-Steensma (2015), marshes serve as natural buffers, mitigating flood risks by creating protective zones in front of sea dykes. This restoration strategy does not only align with adaptation efforts to reinforce coastlines against rising sea levels but also highlights the importance of salt marshes for coastal biodiversity, for example by improving water quality or providing habitats for a variety of species, as emphasized by Graversen et al. (2022). Furthermore, Seiffert and Hesser (2014) argue for salt marsh restoration, emphasizing its significance in mitigating the impacts of sea-level rise while providing crucial habitats for estuarine species and enhancing water quality. Berry et al. (2015) provide evidence supporting the effectiveness of salt marsh restoration, demonstrating improvements in local water quality, stormwater runoff treatment, and acting as a sink for contaminants and nutrients.

Restoration of seagrass meadows is discussed by Ondiviela et al. (2014) as a significant adaptation measure for coastal defense. Seagrasses stabilize sediments, reduce wave energy, and enhance accretion, providing protection against erosion while supporting biodiversity. Recommendations of the study for advancing the use of seagrass meadows in coastal defense include improving our understanding of the ecological and physical processes that drive their protective services, including species-specific traits and ecosystem dynamics affecting service predictability. Addressing knowledge gaps, particularly in understanding the impacts of climatic and anthropogenic stressors on seagrass responses and their interactions, remains essential for enhancing the predictability and effectiveness of this approach. Torres et al. (2021) caution that warming-induced stress threatens the survival of seagrasses and the critical ecosystem services they provide, including adaptation and mitigation benefits as well as biodiversity support. Balestri et al. (2017) advocate for incorporating seagrass meadow restoration into management strategies to bolster coastal resilience in the face of sea-level rise.

Restoration of dunes can mitigate the impacts of sea-level rise and erosion along coastal areas. Laporte-Fauret et al. (2021) investigate the use of notches in foredunes as a restoration strategy to enhance sand accretion and rejuvenate plant communities, thereby contributing to both coastal protection and habitat restoration. The study highlights the need for further research on the effects of coastal dune remobilization on vegetation dynamics and biodiversity, particularly in arid and stressful climates, to optimize these restoration techniques. Esteves (2013) discusses the deliberate creation of new intertidal habitats, including dunes, to improve flood risk management and biodiversity conservation. Schuerch et al. (2022) also highlight dune restoration within managed realignment. Moreover, López-Dóriga et al. (2020) layout the importance of dune restoration within the framework of habitat restoration projects.

Restoration of reefs, specifically oyster and artificial reefs, emerges as a nexus measure for enhancing coastal resilience and supporting biodiversity. Moraes et al. (2022) highlight a project in the Netherlands connecting oyster reefs to marsh edges to enhance the functionality and resilience of both systems for shoreline protection. Ondiviela et al. (2014) discuss hybrid solutions that combine "oyster domes" with seagrass meadows for coastal protection, enhancing habitat complexity, sediment stabilization and wave attenuation. Laporte-Fauret et al. (2021) present a case study where artificial reefs integrated with seagrass meadows increase ecosystem resilience, showing that seagrass production around artificial reefs remains resistant to human stressors.

Finally, several studies stress the importance of adequate monitoring to analyze long-term dynamics and improve the effectiveness of conservation measures aimed at enhancing the resilience of coastal systems (e.g. Derolez et al., 2023; West et al., 2021).

3.3.2 Measures reducing environmental impact

Eleven of the reviewed papers discuss concrete measures to reduce environmental impacts. These measures range from local interventions, such as pollution control and alternative fishing gear, to broader strategies like fisheries regulations and ecosystem-based management at the European level.

Adaptive ecosystem-based fisheries management emerges as a central theme, with studies highlighting sustainable practices to maintain ecosystem resilience in the face of climate change. Merino et al. (2019) and Filho et al. (2022) emphasize the importance of sustainable fisheries management among climate impacts, proposing measures such as catch limits, habitat protection, and ecosystem-based management to ensure the resilience of fisheries and marine biodiversity. Similarly, Woods et al. (2022) highlight a range of ecological, social, and institutional options for improved fisheries management. Moreover, Torres et al. (2021) discuss the improvement of fisheries management regarding species that are most vulnerable to climate change. Cheung et al. (2018) call for adaptive fisheries management and conservation plans that consider the cumulative impacts of climate change and human stressors on marine biodiversity. Ortega et al. (2023) advocate Fisheries Restricted Areas as NbS interventions to improve fisheries sustainability in the Mediterranean region. Payne et al. (2021) emphasize the need to enhance resilience to climate change impacts on fisheries through measures reinforcing social safety nets.

Measures to reduce the environmental impacts of fishing practices are highlighted in several studies. Muñoz et al. (2023) highlight the importance of exploring alternative fishing gear with less impact on the seafloor and measures to reduce the carbon footprint of bottom trawling. This involves investigating gear modifications and selective fishing practices to minimize bycatch of non-target species, as discussed by Cheung et al. (2018). Woods et al. (2022) point out the significance of investing in innovative fishing gear to minimize environmental degradation and improve the sustainability of fisheries.

Pollution reduction and improving water quality are particularly crucial in regions impacted by pollution and eutrophication. Two studies emphasize the importance of improving water quality and combating eutrophication as important management measures. Ahlvik and Hyytiäinen (2015) highlight the economic impacts of eutrophication and stress the significance of adaptive management strategies. Similarly, Takolander et al. (2017) underscore the importance of implementing effective measures to reduce eutrophication, particularly in coastal regions facing compounded challenges from climate change. Restored wetlands, for example, improve stormwater treatment, reduce pollution loads, and increase water retention during extreme weather events (Berry et al., 2015).

3.3.3 Construction and semi-natural measures

Four studies discuss construction-based approaches, encompassing both traditional human-made structural methods and innovative semi-natural or hybrid solutions.

Building of dams across estuaries help mitigate the impacts of storm surges and sea-level rise (Seiffert and Hesser, 2014). These dams narrow the cross-section of the estuary upstream, thereby reducing the potential for inundation. However, the authors note that such structures may inadvertently intensify erosion rates and impact navigation due to increased current velocities near the dam.

Construction and reinforcement of coastal defense structures such as embankments are widely highlighted for their role in in protecting human communities from climate impacts like storm surges and sea-level rise. However, these measures can sometimes disrupt natural processes and negatively affect coastal ecosystems, potentially undermining long-term ecological resilience (Filho et al., 2022; López-Dóriga et al., 2020).

Sediment diversion to flooded back swamp areas is also proposed as a crucial measure for protecting vulnerable coastal regions. This method helps to mitigate sediment deficits caused by sea-level rise by redirecting sediment-laden water, thereby supporting wetland restoration and reinforcing natural coastal barriers (Filho et al., 2022).

Beach nourishment, a process involving the artificial supplementation of sediments, is being advocated to address sediment deficits caused by sea-level rise which is an increasing challenge for the maintenance of coastal structures and ecosystems. Beach nourishment aims to replenish sediment stocks at strategic locations, supporting inter-tidal flats and salt marshes crucial for coastal resilience (Hofstede and Stock, 2018; López-Dóriga et al., 2020).

3.3.4 Stakeholder engagement and communication

A total of 13 studies discuss the importance of stakeholder engagement and communication in addressing climate change impacts and adaptation strategies in coastal and marine environments. These studies emphasize the need for cross-sectoral approaches, inclusive decision-making, and collaborative processes to enhance resilience and support sustainable adaptation measures.

Stakeholder inclusion in decision making processes is a key theme. Thorstad et al. (2021) emphasize stakeholder and cross-sectoral approaches in adaptation implementation (see also Woods et al., 2022). Mokrech et al. (2016) emphasize stakeholder engagement through increased participation in decision-making processes related to climate adaptation. Poumadère et al. (2015) used a scenario workshop with local stakeholders to give policy advice, and Rizzo et al. (2022) used risk analysis as communication tool. Fatorić and Morén-Alegret (2013) emphasize the importance of participatory vulnerability analysis. Simulation models were used to identify adaptation options and discussed with relevant stakeholders (Iglesias et al., 2017).

Integrating social preferences to support sustainable nexus measures is highlighted by Karrasch et al. (2014). They argue that multi-functional land use management enhances coastal community resilience. Key elements for effective adaptation include informal, transparent decision-making, trust-building, and knowledge sharing. West et al. (2021) highlight the importance of understanding stakeholders' diverse decision-making contexts and information needs regarding multiple risks, and advocate for mechanisms that enhance inter- and transdisciplinary communication and mutual understanding in adaptation processes. Howard and Pecl (2019) introduce 'Autochthonous adaptation,' derived from 'cultural adaptation,' which involves communities adapting practices based on their cultural and historical knowledge. It refers to deliberate, locally driven adaptation actions by individuals or small groups, tailored to specific environmental, social, or cultural conditions. The authors highlight the power of combining localized knowledge with scientific insights to build resilience to environmental changes.

Stakeholder inclusion in planning processes seems to be explicitly relevant in the context of the implementation of NbS (see Derolez et al., 2023; Moraes et al., 2022). Tiwari et al. (2022) discuss the benefits of including stakeholders in 'living labs', to facilitate collaboration between stakeholders, researchers, and policymakers in the development of adaptive solutions. However, Iglesias et al. (2017) stress that in communication processes, it is not always possible to ensure that all stakeholder groups are involved for various reasons. Thorstad et al. (2021) highlight the need for more effective communication and collaboration among

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stakeholders to address the diversity of environmental values and ethics that can influence conservation efforts.

4 Discussion

The integration of marine conservation and climate adaptation presents a complex challenge that requires comprehensive, cross-sectoral, and adaptive strategies. This study systematically analyzed 61 publications to elucidate the nexus between marine conservation and climate adaptation in European coastal and marine environments. By categorizing nexus strategies, identifying specific measures, and evaluating the benefits and synergies of these in European temperate shelf seas, we provide a thorough understanding of how integrated efforts can enhance both fields. This discussion synthesizes the key findings, explores the implications of the identified strategies and measures, and offers recommendations while acknowledging the limitations of the current research.

4.1 Outlook on identified nexus strategies

Our review identifies seven types of nexus strategies that address the intertwined challenges of marine conservation and climate adaptation: ecosystem-based strategies, Risk assessment and adaptive management, socio-economic integration, policy and governance mechanisms, Integrated management and planning, and the consideration of trade-offs, conflicts and synergies.

Their frequent combination in the literature underscores the need for holistic strategies that integrate ecological, socio-economic, legislative, and strategic dimensions. Integrating climate adaptation and conservation approaches and measures leverages synergies, enhancing efficiency and effectiveness while addressing both ecological integrity and socio-economic well-being.

Ecosystem-Based approaches leverage natural processes to address climate and biodiversity challenges, offering “no-regrets” solutions adaptable to future scenarios. For example, managed realignment can enhance coastal resilience, support habitat restoration, and mitigate climate impacts. However, success depends on local acceptance and context-specific, long-term planning.

Uncertainties in climate projections and ecosystem responses complicate planning, as ecosystem-based strategies face challenges in predicting effectiveness due to complex interactions and pressures like invasive species. These uncertainties highlight the need for risk assessments, adaptive management, and continuous monitoring. Integrating localized frameworks combining socio-economic indicators with environmental projections can enhance nexus strategies’ precision and impact. The literature’s focus on risk assessment over ecosystem-based strategies underscores the need for comprehensive, solutions-oriented research and greater advocacy.

Effective and coherent governance is essential to unlock the potential of nexus strategies, particularly ecosystem-based approaches. Policies and measures that align climate adaptation and marine conservation objectives can create coherent frameworks for action. Cross-sectoral and transboundary governance reconciles competing interests, fosters socio-economic integration, stakeholder collaboration, and ensures cohesive decision-making across jurisdictions. Enhanced policy alignment ensures mutual reinforcement of adaptation and conservation efforts, aiding strategy development.

Managing trade-offs in approaches like managed realignment illustrates challenges of balancing priorities like habitat restoration vs. community displacement. However, synergies of integrated approaches often outweigh challenges. Thoughtful, context-specific implementation with stakeholder engagement can mitigate negative impacts and enhance positive outcomes.

Success of nexus strategies relies on technical design and processes like stakeholder engagement, adaptive management, and integrated policies. Our findings offer insights into European coastal experiences, highlighting progress and challenges. By synthesizing these, our findings may contribute to the development more integrated marine conservation and climate adaptation strategies. Addressing barriers and knowledge gaps will enhance nexus strategies’ effectiveness, fostering resilient, sustainable coasts capable of withstanding climate challenges.

4.2 Outlook on identified nexus measures

The identified measures fall into four categories: protection and restoration, reduction of environmental impacts, construction and semi-natural solutions, and stakeholder engagement and communication. Their combined application reflects an integrated approach enhancing synergies between conservation and adaptation, boosting effectiveness.

Protection and restoration measures, including MPAs, are crucial for biodiversity conservation and climate adaptation. Strategically designed MPAs prioritizing connectivity enhance resilience by facilitating species migration. Restoration initiatives like wetland and dune restoration build adaptive capacity, supporting resilience.

Reducing environmental impacts includes addressing land-based stressors like eutrophication which supports ecosystem-based measures, highlighting water quality’s importance in mitigating human impacts and promoting sustainable management. Adaptive fisheries management reduces ecological footprints while maintaining resilience. Strategies like adaptive catch limits, alternative gear, habitat protection, and integrating biodiversity considerations contribute to stability.

Construction and semi-natural measures like sediment diversion, vegetative plantings, and beach nourishment integrate engineering with natural processes, aligning climate adaptation with conservation goals. They provide dual benefits for coastal protection and ecosystem health but require careful evaluation of impacts to ensure sustainability and avoid unintended consequences.

Stakeholder engagement and communication are pivotal for successful nexus strategies, fostering trust and social acceptability. Participatory governance integrates local knowledge, improving sustainability and relevance. However, challenges like power imbalances necessitate transparent, equitable decision-making. Building trust is resource-intensive but essential for inclusive, effective outcomes.

4.2.1 Underrepresented Ecosystems and Measures

Our analysis reveals that certain ecosystems including canopy-forming macroalgae, geogenic reefs, and biogenic reefs beyond oyster beds (e.g., mussel beds, coral reefs) are underrepresented as central nexus measures in the European context. This contrasts with studies elsewhere highlighting their roles in reducing wave energy, stabilizing sediments, and enhancing biodiversity. For instance, oyster reefs in the U.S. reduce wave heights by 51–90% and dissipate up to 99% of wave energy (Pfennings et al., 2024); once they dominated European coastlines (Thurstan et al., 2024), but small-scale restoration efforts in the North Sea are trying to recover them. Similarly, kelp forests and rocky reefs mitigate wave energy and prevent erosion (Denny, 2021), yet they are insufficiently explored in European adaptation strategies and reports (Vousdoukas et al., 2020). Despite their transformative potential, these ecosystems' roles as integrated solutions for climate adaptation and marine conservation in Europe appear overlooked. This gap underscores the need to incorporate diverse habitats into NbS and EbA strategies, as recent studies suggest (Galluccio et al., 2024; Perricone et al., 2023). Future research should assess these ecosystems' applicability in nexus strategies and integrate them into NbS frameworks to enhance coastal resilience and multifunctional ecosystem services.

In summary, the studies underscore the intricate links between climate-induced changes, human activities, and the imperative of ecosystem resilience. They offer valuable insights into strategies for mitigating climate change impacts on marine ecosystems and enhancing coastal resilience, all while supporting human well-being through essential ecosystem services and co-benefits. By integrating climate adaptation into existing conservation measures and adopting holistic, context-specific solutions, we can more effectively address the complex challenges posed by climate change.

4.3 Benefits and challenges of nexus strategies and measures

Integrating marine conservation and climate adaptation through nexus strategies and measures offers numerous benefits and co-benefits. These include economic benefits, social resilience, ecosystem resilience, climate protection, coastal protection, and human wellbeing. Nexus strategies demonstrate the practicality and effectiveness of combining conservation and adaptation, however challenges remain. Implementation hurdles, funding constraints, stakeholder conflicts, data gaps, and the need for long-term commitment can impede progress. This section synthesizes the benefits of nexus strategies and measures while addressing the challenges to their effectiveness.

Economic benefits and challenges

Soft adaptation measures like ecosystem restoration create synergies that generate direct and indirect economic benefits, including recreational opportunities, green job creation, local economic stimulation, and prevention of costly climate-related damages (Hoggart et al., 2014). Restoring multiple habitats simultaneously accelerates ecosystem recovery and offers cost-effective solutions (McAfee et al., 2022).

Challenges: Securing adequate funding remains a major hurdle, as restoration requires significant upfront investment with benefits that accrue over the long-term. Additionally, economic benefits may be unevenly distributed, leading to disparities that can fuel stakeholder conflicts.

Social resilience and adaptive capacities

Building social resilience involves enhancing communities' capacity to adapt to environmental changes while maintaining health and well-being. Stakeholder engagement and socio-economic integration - such as community-led coastal management and inclusive policymaking - foster social cohesion and empower communities (Fatorić and Morén-Alegret, 2013). These approaches integrate local knowledge, ensuring interventions are culturally appropriate and socially acceptable.

Challenges: Barriers include power imbalances, competing priorities, and communication gaps, especially in transboundary or heavily used ocean spaces. Adaptive capacities are further constrained by institutional inertia, resource limitations, and social inequities, which weaken resilience in marginalized groups. Transparent, just decision-making and conflict resolution mechanisms are essential to overcome these barriers.

Ecosystem resilience and implementation barriers

Nexus measures such as habitat restoration and managed realignment strengthen ecosystem stability and resilience by enhancing biodiversity and supporting ecological functions. Reducing pressures, including overfishing and habitat destruction from fishing activities, helps ecosystems recover from disturbances and maintain ecological balance (Muñoz et al., 2023).

Challenges: Restoration faces technical difficulties, such as selecting appropriate species and ensuring survival rates, alongside regulatory hurdles and coordination gaps among agencies. Limited data on ecosystem responses to restoration and climate change (e.g., rarely quantified biodiversity net gains and costly biodiversity inventories) hinder accurate outcome predictions, emphasizing the need for adaptive management and improved monitoring.

Climate mitigation potential

Many nexus measures enhance carbon sequestration and regulate greenhouse gas emissions. Coastal habitats such as salt marshes are particularly effective carbon sinks, contributing significantly to climate regulation (Seiffert and Hesser, 2014). Minimizing pressures like overexploitation and habitat destruction (e.g. from bottom trawling) helps maintain the ocean's ability to absorb carbon dioxide.

Challenges: Measuring these benefits is complicated by inconsistent methodologies and data limitations for assessing long-term carbon sequestration in marine ecosystems, creating uncertainties. Greater investment in research and monitoring is essential to inform evidence-based policies and ensure the long-term success of climate mitigation efforts.

Coastal protection potential

Natural defenses like restored wetlands and managed realignment buffer coastal zones against storm surges, sea-level rise, and erosion, mitigating extreme weather impacts (Graversen et al., 2022).

Challenges: The benefits of these measures often take time to materialize, requiring sustained commitment from stakeholders and policymakers. Short-term political cycles and funding periods can conflict with the long-term nature of ecosystem restoration, risking discontinuity. Ensuring lasting efforts necessitates robust institutional frameworks and secure, dedicated funding streams.

Health, well-being, and other societal challenges

Healthy marine and coastal ecosystems enhance human health and well-being by supporting food security, offering recreational opportunities, and providing cultural value (Sandifer et al., 2015). They also improve environmental quality by trapping contaminants and nutrients, purifying water, and reducing natural disaster risks, which contributes to better physical and mental health outcomes (Aronson et al., 2016).

Challenges: The benefits are often undervalued in economic assessments, leading to underinvestment. Furthermore, access to these benefits may not be equitable across different societal groups, raising issues of environmental justice that need to be addressed through inclusive policies.

The nexus strategies and measures offer significant opportunities for enhancing marine conservation and climate adaptation simultaneously while achieving multiple co-benefits, underscoring the interconnectedness of ecological, social, and economic systems. Realizing their full potential requires implementing them to maximize synergies and addressing the inherent challenges. While these can transform nature management and deliver substantial ecological and societal benefits, their effectiveness depends on appropriate regulations and enabling conditions, such as adequate resources, policy instruments, and community involvement.

The challenges identified highlight the need for strategic planning and adaptive management. For instance, Lotze et al. (2022) call for a proactive approach to tackle current and projected climate change impacts. Prioritizing protection of areas shielded from climate change effects (climate-change refugia) is identified as a critical strategy to ensure the persistence of valued ecosystems and their services (Morelli et al., 2020). Overcoming barriers like implementation challenges, funding constraints, stakeholder conflicts, and data limitations requires collaborative efforts that integrate scientific research, community engagement, and policy innovation to advance sustainable and resilient marine ecosystems and communities.

The body of literature left gaps in empirical studies that demonstrate the long-term outcomes of integrated strategies and an under-representation of socio-economic dimensions in practical applications. Furthermore, literature lacks specific methods systematically integrating adaptation strategies into existing marine conservation frameworks at a regional scale.

4.4 Recommendations

The body of research reviewed herein underscores the imperative for integrated frameworks that go beyond habitat- or infrastructure-specific measures to align with broader climate adaptation and resilience goals. Despite substantial evidence supporting the effectiveness of ecosystem-based approaches as solutions to climate change and other societal challenges, gaps remain in translating these insights into cohesive policies and management strategies that fully harness measures like ecosystem restoration. This synthesis not only informs current practices but also encourages new research and decision-making processes that prioritize holistic, adaptive solutions to meet the challenges of a changing climate.

To further enhance effectiveness, uptake and upscaling and of nexus strategies and measures, we propose the following recommendations:

1. Implement and scale tailored ecosystem-based approaches

   To enhance the resilience of coastal and marine ecosystems, ecosystem-based approaches (including NbS and EbA) must be tailored to the unique ecological characteristics of specific regions and sites while holistically addressing cumulative pressures. Employing ecosystem-based and precautionary principles using a social-ecological system approach involves identifying and mitigating cumulative pressures across the entire system, promoting biodiversity by reducing environmental stressors such as eutrophication and eliminating harmful activities like unsustainable fishing. These pressures must be understood, assessed, and mitigated simultaneously through cause-and-effect analyses and adaptive management (Elliott et al., 2017; Sánchez-Arcilla et al., 2016).

   Scaling up ecosystem-based approaches requires designing, implementing, and monitoring interventions based on best practices, such as the IUCN Global Standard for NbS (IUCN, 2020). Stronger policy actions and increased funding are needed to support NbS for coastal and marine adaptation, including restoring natural processes, promoting ecosystem-based management, and developing innovative technologies and materials. By combining ecosystem-based approaches at scale, multiple policy objectives can be achieved, including Good Environmental Status (GES) under the MSFD, while enhancing social-ecological resilience. Key priorities include focusing on high-impact areas where nature-based solutions provide the greatest co-benefits for biodiversity, climate adaptation, and community resilience. To ensure long-term effectiveness, these approaches must be fully embedded in sectoral policies, backed by sustained funding, and supported by strong governance frameworks. These strategies not only enhance biodiversity and ecosystem functionality but also align with broader sustainability and climate goals.

2. Optimize spatial protection and restoration for climate-resilient ecosystems and communities

   Design and manage coastal and marine protected areas to enhance their climate adaptation and mitigation potential by protecting and restoring carbon-sequestering and climate-buffering habitats, strengthening thermal and climatic refugia to reduce ocean warming impacts, and maintaining ecological connectivity to facilitate species range shifts and adaptive responses. Establishing well-connected and effectively managed MPAs maximizes biodiversity conservation while addressing climate impacts. Ensuring sufficiently strict protection, particularly in ecologically valuable locations and high-pressure areas, is crucial for sustaining ecosystem services that would otherwise be degraded or lost (Aminian-Biquet et al., 2024). Minimizing exploitation of coastal areas is necessary to prevent activities undermining ecological recovery and conservation goals. Optimizing spatial protection through systematic conservation planning (SCP) and dynamic management further enhances these outcomes. Prioritizing areas with high socio-ecological resilience potential should guide conservation and adaptation efforts, particularly in ecosystems where natural regeneration is hindered and in high-risk coastal regions, helping prevent both ecological degradation and socio-economic losses associated with environmental change. Adaptive spatial protection and restoration measures, responsive to dynamic climate and ecosystem conditions, can increase cost-effectiveness, prevent ecosystem service loss, and enhance socio-economic benefits by supporting sustainable livelihoods and local community resilience. This requires the use of flexible management strategies, such as temporal or spatial closures, with conservation measures continuously adjusted based on ongoing monitoring and climate projections (Vigo et al., 2024). Incorporate restoration into spatial protection schemes to account for habitat-specific benefits, time lags in ecosystem recovery, and the need for sustained management to ensure lasting impacts. MSP must fully align with ecosystem-based principles to reduce stressors and support ecosystem resilience, yet to achieve this persistent implementation challenges in governance and socio-ecological integration must be addressed (Galparsoro et al., 2025). Strengthening the ecosystem approach in MSP and ICZM can balance resource demands with environmental protection, delivering synergistic outcomes for adaptation, mitigation, and biodiversity conservation.

3. Strengthen integrated, cross-sectoral and transboundary governance

   Building robust cross-sectoral governance structures is essential to coordinate efforts, secure funding, and maintain long-term commitments beyond political cycles. Policies should ensure that marine conservation and climate adaptation strategies evolve together under EU and member state frameworks, incorporating adaptive measures for future climate scenarios. Achieving effective policy and management integration requires aligning policies with practical actions through instruments that support implementation, ensure compliance, and strengthen enforcement. Achieving resilient and adaptive coastal-marine ecosystems in Europe requires stronger regulatory coherence between different marine related governance attempts, like the MSFD, NRR, MSPD, and the CFP. While each policy contributes to marine conservation and climate adaptation, their fragmented implementation have limited their collective impact (Kyrönviita et al., 2024). Addressing these governance gaps requires an integrated approach that enhances cross-sectoral coordination, enforcement, and long-term financial sustainability. By aligning the different objectives, the EU can ensure that marine conservation and climate adaptation are mutually addressed. Transboundary cooperation across sea basins and between EU member states should be supported to adopt more joint management of cross-border marine ecosystems such as the Trilateral Wadden Sea cooperation. Regional frameworks like OSPAR and HELCOM provide established mechanisms for coordinating efforts in the North-East Atlantic and the Baltic Sea, respectively, but could play a stronger role in fostering collaboration on climate adaptation and conservation by enhancing cross-border collaboration on ecosystem-based approaches. Similarly, the Mediterranean Protected Areas Network (MedPAN) supports MPA coordination, and strengthening its role in facilitating transboundary management, knowledge exchange, and adaptive conservation could improve regional climate resilience and conservation outcomes. In addition, redesigning governance frameworks to integrate local insights and coordinated risk-response strategies to climate impacts and standardizing data collection methods and sharing best practices will benefit both climate adaptation and marine conservation efforts, facilitating a cohesive regional approach.

4. Enhance stakeholder engagement and consider equity

   Engaging coastal communities, fisheries, and other stakeholders in the decision-making process is crucial to ensure that adaptation strategies are socially equitable and economically viable. Engaging relevant sectors and stakeholders in integrative planning and incentivizing sustainable practices can foster behavioral shifts that support societal goals and a resilient, well-protected marine environment. Addressing power imbalances is critical for facilitating inclusive participation, building trust, and mitigating conflicts, thereby ensuring fair distribution of benefits and responsibilities. To achieve this, participatory governance models and community-based management should be implemented, empowering stakeholders and integrating diverse perspectives into planning and implementation processes. Decision-support tools should enable stakeholders to evaluate trade-offs between protection and restoration for specific ecosystems, ensuring alignment with societal goals and risk minimization. Additionally, leveraging storytelling and the arts can effectively engage and inspire communities beyond policy changes or incentives alone. By combining these strategies, policies can foster inclusive participation and equitable benefits, ultimately enhancing the resilience and sustainability of marine and coastal ecosystems.

5. Strengthen long-term monitoring and funding

   Standardized methodologies to assess the benefits and trade-offs of nexus measures are essential for comparability and evidence-based decisions. Cross-EU data standardization and knowledge-sharing should be strengthened to support coordinated marine conservation and climate adaptation. Monitoring efforts should evolve into integrated, real-time systems that link environmental, social, and economic indicators, ensuring adaptive management based on up-to-date insights. Establishing consistent, long-term monitoring frameworks across EU marine regions will improve comparability and policy integration while enabling dynamic responses to emerging climate and biodiversity challenges.

   Investing in ecological and social monitoring is key to closing data gaps, improving predictive models, and scaling large-scale, cost-effective restoration. Innovative funding mechanisms, such as payments for ecosystem services, blue bonds, and public-private partnerships, must be expanded to sustain these efforts. To scale up effective marine conservation and climate adaptation, financial and legal frameworks must work in tandem. Unlocking long-term funding requires integrating nature-based finance from public and private sources, leveraging blue carbon markets, and ensuring alignment with the EU Taxonomy for sustainable activities. This should complement existing funding streams such as EU LIFE, Horizon Europe, and the European Maritime, Fisheries, and Aquaculture Fund (EMFAF). Demonstrating success through lighthouse projects can showcase the tangible benefits of nexus strategies and measures, attracting further investment and inspiring wider implementation. Embedding socio-economic benefits into marine conservation and adaptation strategies will not only enhance financial viability but also drive effective policymaking.

6. Advance interdisciplinary research and innovation

   Tackling the challenges of climate change, biodiversity loss, and human activities in European seas requires stronger interdisciplinary collaboration that connects natural sciences, social sciences, and practical applications. Research efforts need to move beyond siloed approaches to ensure that knowledge is shared and applied effectively in conservation and adaptation efforts. Expanding cross- and transdisciplinary dialogues through co-creation workshops that bring together ecologists, climate scientists, economists, maritime industries, and local communities can help develop more integrated approaches. Establishing permanent platforms for knowledge exchange beyond individual project timelines or shifts in policy and funding priorities would support ongoing interaction between researchers and practitioners in marine conservation and climate adaptation. Strengthening cooperation between marine research institutes and applied sectors such as fisheries, tourism, and offshore energy can improve the alignment of scientific knowledge with sector-specific sustainability goals. To maximize conservation impact, research should focus on areas where ecosystem-based approaches provide co-benefits for climate adaptation, biodiversity conservation, and sustainable resource use. This requires transformative interdisciplinary research to develop adaptive, stakeholder-driven solutions. By reshaping conservation and adaptation strategies through co-designed, solution-oriented research, the EU can foster greater resilience in its seas while ensuring that science effectively informs policy and practice. Additionally, financial mechanisms that support interdisciplinary research in marine and coastal regions should be adjusted to facilitate long-term collaboration and applied innovation.

4.5 Limitations

Among limitations of our study is the reliance on expert judgment to categorize publications and extract nexus strategies, which may introduce subjectivity into the analysis. Additionally, the scope of the core literature systematically reviewed in this study was limited to peer-reviewed publications, potentially overlooking relevant grey literature and non-English language sources that could provide valuable insights on the nexus. This limitation may have restricted the comprehensiveness of the findings. While the list of measures provides a good overview of potential measures to address issues relating to coastal and marine protection as well as climate adaptation, it is not exhaustive. Our exclusion criteria, which focused on the discussion of the marine conservation and climate adaptation nexus, may have omitted papers that discuss relevant measures without explicitly addressing the nexus approach.

5 Conclusion

Our review highlights a gap in the integrated study of marine conservation and climate adaptation. While extensive research exists on each field individually, there remains a scarcity of knowledge in understanding how they can be effectively interlinked. This gap likely corresponds to a deficiency in application and practical implementation of nexus approaches, which are still in the early stages of development (Liu et al., 2018). The identification of potential trade-offs underscores the importance of considering the unintended consequences of adaptation strategies and the need for integrated decision-making processes.

By identifying and categorizing nexus approaches and measures in Europe's marine and coastal environments, our study aims to bridge this gap. Effective implementation of these approaches can mitigate negative impacts, enhance coordination in planning and governance, and examine cross-scale dynamics among governance realms and sectors. Nexus strategies leverage synergies and manage trade-offs to balance diverse environmental and social objectives. Highlighting present approaches, identifying gaps and proposing actionable solutions, we advance the understanding and application of strategies that build the resilience of social-ecological systems under climate change. Transformative change is achievable through coherent collaboration among policymakers, researchers, and stakeholders to embrace and implement these integrated strategies.

Author contributions

GF: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. FK: Data curation, Formal Analysis, Writing – original draft, Writing – review & editing. NS: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. CS: Conceptualization, Data curation, Investigation, Writing – original draft, Writing – review & editing. MS: Conceptualization, Data curation, Formal Analysis, Methodology, Validation, Writing – original draft, Writing – review & editing.

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Conflict of interest

Author CS was employed by AquaEcology GmbH & Co. KG.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript.

ChatGPT (www.chatgpt.com) was used for minor language editing and text refinement, with all outputs thoroughly reviewed and verified by the authors to ensure accuracy and integrity. Napkin AI (www.napkin.ai) was utilized to create Figures 2, 3, based on the authors' ideas.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2025.1542705/full#supplementary-material

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