Deliverable D3.1- *Revision and practical guidelines for the implementation of innovative ecological and environmental concepts in MPA processes*

WP3 – Work Package 3

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Document History

Deliverable Title	Revision and practical guidelines for the implementation of innovative ecological and environmental concepts in MPA processes
Brief Description	This deliverable outlines how ecological and environmental data are used to support MPA processes. It reviews academic and grey literature relevant to MPAs to identify best practice guidelines, what European MPAs achieve in practice, and how the reality for practitioners maps across with recommendations from theoretical ideals. The deliverable also provides a framework to operationalize the use of ecological and environmental data to support MPA processes, and highlights the state-of-the-art knowledge.
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Author(s)	George Hoppit (UCD), Kristiina Nurkse (UTARTU), Robert Szava-Kovats (UTARTU), Annaïk Van Gerven (RBINS), Anneliis Kõivupuu (UTARTU), Martha Stevens (VLIZ), Annaleena Vaher (UTARTU), Imtiyaz Beleem (UTARTU), Nemanja Malovrazić (MRT), Guillaume Marchessaux (UNIPA), Francesca Frau (MEDSEA), Maëlla Sicard (OFB), Kora Dvorski (WWF Adria), Ana Krvarić (WWF Adria), Myriam Johanna Perschke (SDU), Susanna Jernberg (SYKE), Kaisa Raatikainen (SYKE), Nicoletta Cadoni (MEDSEA), Francisco R. Barboza (UTARTU)
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1. Executive Summary

Work package 3 is developing science-based tools for ecological and environmental solutions under an operational framework for the ecology-based design and management of local MPAs and regional MPA networks across European seas. This deliverable explores how ecological and environmental data are used to support MPA processes. Using a combination of evidence collected from academic and grey literatures, we performed a gap analysis. We identify the best practices recommended for MPAs and see how European MPAs have adopted or failed to adopt these. An operational framework for incorporating novel knowledge was generated, proposing a change from static and spatially restrictive MPA processes focusing only on structural components of marine ecosystems to temporally dynamic and spatially integrative processes incorporating functional aspects. This operational framework provides foundational components for future actions in the frame of Work Package 3 (Task 3.2 and 3.3) looking at developing decision support tools for the effective incorporation of the best available ecological and environmental knowledge and data into European MPA processes.

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2. Introduction

This deliverable aims to identify how ecological and environmental data is integrated into European MPA process. This will provide the foundational knowledge required for Work Package 3 to identify, develop, test, recommend, and implement decision support tools for European MPA design and management. In the next sections, we frame the need to better protect European marine ecosystems through MPAs, how we identify current approaches to using ecological and environmental data in the Blue4All Living Labs (LL) and Information Sites (IS), and the best practices recommended by the scientific literature. We complement this using gap analysis to identify how European MPAs compare with recommended best practice. We conclude by examining how to operationalize the use of ecological and environmental knowledge and data to better support European MPA processes.

2.1 The reality and protection of European Marine Ecosystems

Global marine environments face many degrading factors, including climate change, overfishing, pollution, and habitat destruction. These pressures are causing significant declines in marine biodiversity, disrupting ecosystems, and threatening the livelihoods of communities that depend on the sea (Andrews et al., 2021; Talukder et al., 2022; Duarte et al., 2020). The urgency to address these issues is paramount as the loss of marine ecosystems not only jeopardizes marine life but also impacts global food security, economic stability, and the overall health of the ecosphere (Barnard et al., 2021; Winther et al., 2020). Immediate and comprehensive measures are necessary to mitigate these impacts and preserve the intricate balance of marine life, with Marine Protected Areas (MPAs) being advocated as promising remedial measures for the threats faced by marine environments (Grorud-Colvert et al., 2021; Maxwell et al., 2020; Sala et al., 2021).

In Europe, the continent's marine ecosystems are viewed as among the most anthropogenically impacted and depleted seascapes on Earth (Bekkby et al., 2020; Dailianis et al., 2018). This is due to historical resource extraction and rapid development of coastal areas, poor regulation and limited coordination between member states (Fraschetti et al., 2018). To promote European political ambitions for nature conservation, UN sustainable development goals, and national ambitions for restoring deleted ecosystems, it is paramount that European marine ecosystems are housed within effective MPAs (Katsanevakis et al., 2020).

Internationally, numerous directives and regulations have been established to safeguard marine environments, reflecting a growing recognition of the need for coordinated action to address marine conservation challenges (Duarte et al., 2020). Key frameworks include the United Nations Convention on the Law of the Sea (UNCLOS), which sets out legal principles for the use and protection of marine resources, and the Convention on Biological Diversity (CBD), which includes specific targets for marine and coastal biodiversity. Additionally, the Sustainable Development Goals (SDGs), particularly Goal 14 ("Life Below Water"), call for the conservation and sustainable use of

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oceans, seas, and marine resources. These international agreements provide a foundational framework for nations to develop and implement marine conservation policies.

In Europe, the regulatory landscape for marine conservation is shaped by several key directives and regulations that set ambitious targets for the protection and sustainable use of marine environments. Central to European conservation and protected area establishment are the Birds and Habitats Directives, which form the legal backbone of the Natura 2000 network – comprising Special Areas of Conservation (SACs) and Special Protected Areas (SPAs). Additionally, the Marine Strategy Framework Directive aims to achieve Good Environmental Status of the EU's marine waters and protect the resource base upon which marine-related economic and social activities depend, as outlined by the regulations work completed in Work Package 1. The Common Fisheries Policy (CFP) seeks to ensure that fishing and aquaculture are environmentally, economically, and socially sustainable. Lastly, the EU Biodiversity Strategy for 2030 aims to place ecosystems on a recovery trajectory by 2030. Together, these European directives and regulations create a comprehensive top-down regulatory framework for marine conservation, promoting collaborative efforts among EU member states to maintain healthy and resilient marine ecosystems.

2.2 The need for better Marine Protected Areas

Area-based protection measures, particularly MPAs, are critical strategies for preserving the integrity of marine ecosystems. The IUCN defines these as "*any area of intertidal or sub-tidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment*" (Kelleher, 1999). In Europe, the implementation of MPAs has been guided by the European Union's Marine Strategy Framework Directive and the Natura 2000 network (under the Birds and Habitats Directives), aiming to achieve good environmental status for marine waters.

The effectiveness of MPAs can be hampered by shortcomings and challenges. Ecological benefits (Duarte et al., 2020; such as protection of biodiversity, refuge areas, and recovery of depleted populations) provided by MPAs often depend on their adequate design and placement (Carr et al., 2017; Turnbull et al., 2021; Gaines et al., 2010), coupled with sufficient monitoring and understanding of the effects of human activities both inside and around the area, along with the monitoring of conservation outcomes targeted by the implementation of the original protection (Dunham et al., 2020; Kachelriess et al., 2014). MPAs require adequate enforcement and management, which can be lacking due to insufficient ecological and environmental knowledge and data to support informed decisions, funding, political will, or community support (Ban et al., 2017; Grorud-Colvert et al., 2021; Gill et al., 2017). This highlights the necessity for a bottom-up approach in MPA processes, ensuring that local stakeholders are engaged and that their needs and knowledge are effectively integrated into the design and management of area-based protection measures (Gaymer et al., 2014).

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The benefits of MPAs only materialize when they are effectively designated, managed, and designed (Grorud-Colvert et al., 2021; Duarte et al., 2020). In Europe, progress has been made in establishing MPAs within the continent's sea basins (Li and Jay, 2020). However, practitioners fear that MPAs will turn into 'paper parks' that deliver negligible or no conservation benefits, either to ecosystems or communities whose livelihoods are dependent on the sea (Álvarez-Fernández et al., 2020). In recent years, the integration of ecological and environmental knowledge in the design and management of MPAs in Europe has become increasingly crucial (Katsanevakis et al., 2020). This is to help address issues like climate change and support ambitions to prevent and reverse the decline of ecosystems. Advances in scientific knowledge, data collection, and analytical techniques over the past two decades highlight the necessity to reassess how these insights are incorporated at various stages of MPA planning and execution (O'Regan et al., 2021). Historically, MPA designs have often been spatially restrictive, focusing on limited geographic areas without accounting for the broader ecological connectivity (Hays et al., 2020; Sullivan-Stack et al., 2022). This narrow approach fails to consider the dynamic nature of marine ecosystems, which are influenced by species migrations, ocean currents, and changing climatic conditions. Typically, MPAs are managed with a temporally static perspective, disregarding seasonal variations and long-term ecological and environmental changes shifts (Kriegl et al., 2021). Such static approaches can undermine the resilience of MPAs to environmental changes and reduce their effectiveness in biodiversity conservation (Holyoak et al., 2020).

Traditional MPA frameworks have been biased toward specific conservation targets, often prioritizing certain species or habitats while neglecting others (Bianchi et al., 2022). This species-oriented approach can lead to gaps in protection and may not fully address the complex interdependencies within marine ecosystems (Radinger et al., 2023). To enhance the efficacy of MPAs, it is essential to adopt more holistic and adaptive management strategies that integrate comprehensive ecological data and predictive modeling (Grorud-Colvert et al., 2021; Mahrad et al., 2020). More holistic approaches will also better help identify areas for protection. By leveraging the state-of-the-art scientific insights generated over the last two decades, policymakers can design MPAs that are not only spatially and temporally flexible but also ecologically inclusive (Duarte et al., 2020; Katsanevakis et al., 2020). This will ensure that MPAs can better respond to environmental changes, support diverse marine life, and sustain ecosystem services crucial for both biodiversity and human wellbeing.

2.3 Work Package 3 of Blue4All

The goal of Work Package 3 (WP3) is to identify how to better integrate ecological and environmental knowledge and data into European MPA processes. By doing so, WP3 aims to enhance the decision-making frameworks that govern MPAs, ensuring that they are based on the best knowledge and data available. This integration is critical for the effective management and conservation of marine ecosystems, as it enables policymakers and practitioners to develop strategies that are better informed, adaptive, and responsive to the dynamic nature of marine

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environments. Additionally, WP3 seeks to bridge the gap between scientific research and practical application, thereby fostering a more sustainable and resilient approach to marine conservation efforts. WP3 not only supports the protection of biodiversity but also promotes the sustainable use of marine resources, aligning ecological priorities with environmental management practices.

Task 3.1 explores ecological concepts well-established in the academic bibliography but generally overlooked in European MPA processes, and the practical implementation of these innovative concepts for the management of existing MPAs and designing future sites and networks. This deliverable specifically reports on providing the foundational knowledge base for easy-to-use information that supports MPA processes. Specifically, how ecological and environmental data dimensions support the effective design and implementation, and management of the Blue4All Living Labs (LL) and Information Sites (IS), considering both individual MPAs and MPA networks across European Sea Basins.

We asked how ecological and environmental data is used to support European MPA processes. Ecological and environmental data play a pivotal role in informing and guiding the establishment, management, and conservation strategies of MPAs. Such data provide invaluable insights into the ecological dynamics, species distributions, habitat conditions, and overall health of marine environments. By leveraging various ecological and environmental data sources, including satellite imagery, field surveys, biodiversity assessments, and ecological modelling, stakeholders can gain a comprehensive understanding of marine ecosystems and the factors influencing their functioning. Task 3.1 specifically looks at four sub questions:

- How does ecological and environmental knowledge and information support MPA policy and practice in Europe?
- What is the nature of ecological and environmental knowledge and information currently integrated into European MPA processes, and what has been suggested in the specialized bibliography?
- When and how in the European MPA process has this knowledge and information been incorporated?
- What recommendations/lessons have been given/learnt and what challenges have been faced by trying to integrate ecological and environmental knowledge and information into European MPA processes?

Numerous academic papers and research studies explore the utilization of ecological and environmental data in relation to the processes and functionality of MPAs (e.g., Katsanevakis et al., 2020; Kriegl et al., 2021; Bekkby et al., 2020; Bianchi et al., 2022; Carr et al., 2017). These works explore various aspects, such as knowledge integration and data collection methods, the impact of environmental drivers and human pressures on MPA effectiveness, and the role of ecological data in shaping conservation strategies. However, despite the wealth of information available, there is a

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notable lack of centralization of this knowledge. The insights and findings are dispersed across multiple sources, making it challenging for researchers and policymakers to access and synthesize the information comprehensively. To the best of the knowledge of this Work Package, no single document has specifically addressed the overarching question of how to integrate these diverse data streams into a cohesive framework that directly supports MPA processes. While the integration and use of comprehensive data might exist in some countries, these are likely to context specific for generalization across wider Europe. This gap underscores the need for a dedicated effort to consolidate existing research and provide a unified approach to leveraging ecological and environmental data for the enhancement of MPA functionality and management.

This information will be instrumental in supporting the development of innovative tools designed to account for the ecological and environmental dimensions in European MPA and MPA network processes. By leveraging this data, WP3 aims to enhance the relevance and effectiveness of tools used in MPA planning, designation, management and reviewing, ensuring they are equipped to consider the complexities of marine ecosystems comprehensively. Additionally, the information will help identify how existing data and information are currently integrated into MPA processes, pinpointing the specific areas and stages where this integration occurs. This analysis will also highlight any key gaps or deficiencies, providing a clear understanding of where improvements are needed. By addressing these gaps, this deliverable will contribute to the creation of more robust and comprehensive tools, ultimately leading to better-informed decision-making and more effective conservation strategies within MPAs.

2.4 How does this support well-managed Marine Protected Areas?

Part of Blue4All’s objectives is to develop enhanced practices for MPA management within the LL. This goal is pursued through the creation of a suite of advanced management tools. These tools are not developed in isolation but are co-created in collaboration with MPA managers and relevant stakeholders, ensuring that they are tailored to the practical needs and challenges faced by those on the ground. This collaborative approach is crucial for fostering ownership and ensuring the relevance and effectiveness of the tools. It also significantly increases the likelihood that these tools, along with the broader results of the Blue4All project, will be adopted and utilized within European MPAs both during and after the project's conclusion, supporting Blue4All’s legacy. This sustainable uptake is vital for achieving long-term improvements in MPA management practices.

In addition to tool development, Blue4All places a strong emphasis on identifying both the state-of-the-art best practices as recommended in the scientific literature and the practical realities of how ecological and environmental data are currently utilized within European MPAs. This comprehensive assessment, undertaken in Task 3.1, is essential for pinpointing weaknesses and gaps in existing MPA designation and management processes. By understanding where current practices fall short, the project can provide targeted recommendations and innovations to address these deficiencies. These efforts form a cohesive strategy aimed at enhancing the effectiveness and

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sustainability of MPAs across Europe. The insights gained from this work will not only inform the development of new tools and practices but also contribute to a deeper understanding of the challenges and opportunities in MPA design and management, ultimately leading to more robust and resilient marine conservation efforts.2.5 How the aims of this deliverable were addressed

To meet the aims of Deliverable 3.1, we devised a three-phase approach (Figure 1). The first phase involved a review of the available literature on how MPAs have been suggested to or implemented ecological and environmental knowledge and data into different processes.

In the second phase, using the literature gathered, we performed a gap analysis to collect data on the current MPA performance, processes, or conditions that enable or use different types of ecological and environmental data. This gap analysis also helped identify how well the scientific bibliography on MPAs are actioned within European sea basins through Blue4All's Living Labs and Information Sites. Using this, we identified the best practices recommended by experts and MPA practitioners. Best practices will be identified and outlined in the final section (Section 5) of this deliverable.

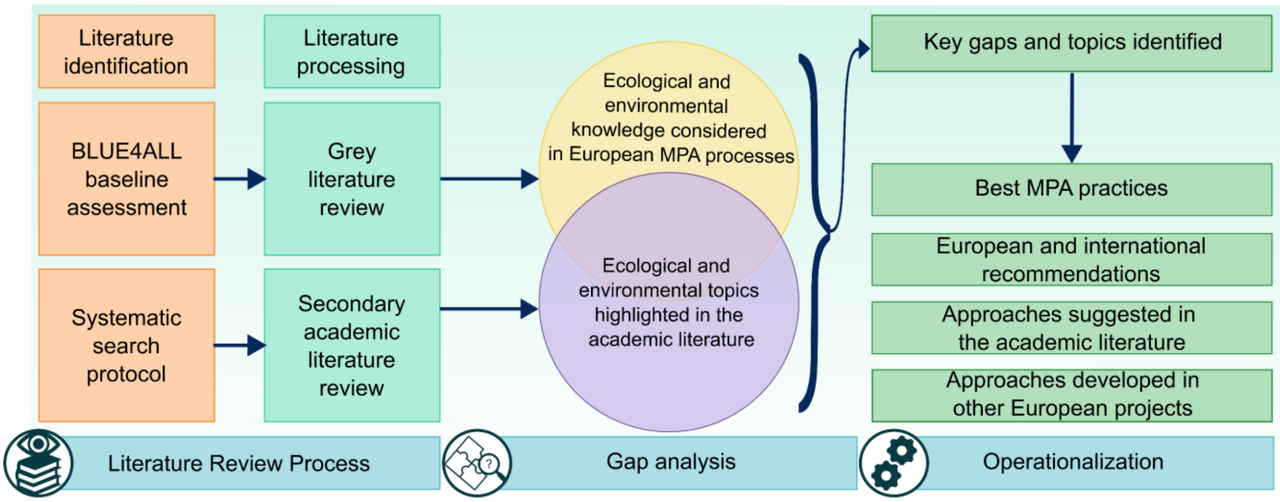

Figure 1. Three-phase approach used to generate the evidence underlying Deliverable 3.1.

The last phase, using the information gathered through the examination of both grey and academic literatures supporting the gap analysis, outlines our proposal for better operationalization of ecological and environmental data and knowledge to support MPA processes. This involved a critical examination of the key topics identified through gap analysis and literature review.

3. Methods

This deliverable conducted a gap analysis based on a review of scientific reviews and a detailed screening of the information provided in official documents of the MPA processes in LL and IS, following the process of Figure 1. We aimed to compile and integrate information gathered from project IS and LL to provide essential and easy-to-use ecological and environmental knowledge for MPA processes.

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The following sections outline the steps taken to identify official documentation (sections 3.1 and 3.2), and the review of peer-reviewed academic literature (section 3.3). The remaining section (3.4) details our approach to standardize and synthesis these literatures to perform the gap analysis which directly feeds into our recommendations for operationalizing key findings and identifying best practice.

3.1. Baseline assessment survey

In October-November 2023, WP4, in collaboration with WP2 and WP3, developed a comprehensive questionnaire to collect baseline understandings of Blue4All's Information Sites (IS) and Living Labs (LL). A lengthy preparatory process occurred, with WP4 leading the refinement, design, and testing of initial questions to ensure the quality of information returned. The final questionnaire design had three parts, focusing on the social, economic, and ecological components of the Blue4All IS and LLs. For this deliverable's purpose, we will concentrate solely on the information pertinent to WP3's scope – the use of ecological and environmental data in MPA processes.

In November 2023, WP4 colleagues distributed the questionnaire to the contact points of IS and LL. By March 2024, all surveys had been completed and returned. The timeline and an implemented strategy were decided based on several reasons. Firstly, it was necessary to create a well-structured questionnaire that addressed the requirements of both WP2 and WP3, thereby clearly informing project goals and minimizing unnecessary interactions with IS and LL. Secondly, ensuring that the questionnaire was comprehensive enough to encompass all necessary content for informing related tasks was crucial, while also avoiding redundant or irrelevant questions. The collaboration between WP4, WP2, and WP3 ensured that the questionnaire was designed to address the diverse needs of the project while being sensitive to the workload of stakeholders. This careful planning and collaboration ultimately resulted in a valuable tool for gathering essential baseline data on the ecological, environmental, and socio-economic aspects of MPA processes.

For WP3, this questionnaire aimed to establish an initial baseline on several critical aspects. Firstly, it focused on the ecological and environmental realities of IS and LLs. Secondly, it explored how ecological and environmental knowledge and data have been integrated into various phases of MPA processes. Thirdly, it examined the extent to which decision support tools, if any, have been employed to guide MPA processes across Europe.

In WP3, we decided to ask MPA practitioners to direct us towards management and technical documents produced by MPAs or used to support their designation and/or ongoing management – termed grey literature in the context of this deliverable. The needed data was later extracted by Project Partners to minimize the time needed on the respondent's part to locate information (which can often be buried deep in dense reports, and not readily known to the level of detail we required for this deliverable). The grey literature was written in local languages and needed translation. It was decided that WP3 would use the diversity of the languages spoken by Project Partners to

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conduct the translation. The following section (3.2) provides detail on the grey literature data extraction process.

3.2. Grey Literature

3.2.1 Grey literature identification

The completed Baseline Assessment Survey directed Task 3.1 partners to grey literature representative of MPAs within the wider European sea basins. Part of the Baseline Assessment Surveys asked individuals filling in the questionnaires to either directly provide, or direct contact points towards framing and management documents used for Blue4All MPAs and MPA networks. The grey literature specific to this task was framing documents and management and monitoring plans for MPAs and MPA networks for the Living Labs and Information Sites. This grey literature was compiled and initially screened by WP3 task leads before dissemination to Project Partners. Project Partners also complemented this process by identifying additional materials if necessary to locate the information necessary for this deliverable. This was due to some surveys returning irrelevant documentation like local legislation which was not useful for the data we hoped to collect, or providing links that could not be accessed.

Collected MPA management documents were written in local languages or housed in regional repositories. Therefore, we established a group of core partners fluent in the languages needed to translate the texts and, if necessary, locate additional information and documentation not identified through the Baseline Assessment Surveys. Grey literature translation required people fluent in French, Dutch, Danish, Italian, Croatian, Swedish, and Estonian. Literature had been directed to the Irish contact point in English, but on examination, this material was unsuitable for our needs.

Grey literature identified covered 3 major European sea basins explored in the Blue4All project; the Baltic, the Northeast Atlantic, and the Mediterranean (Figure 2). Additionally, the returned documentation covered single MPAs, portions of MPA networks, and MPA networks, ensuring we had good coverage of the key MPA configurations within the European region.

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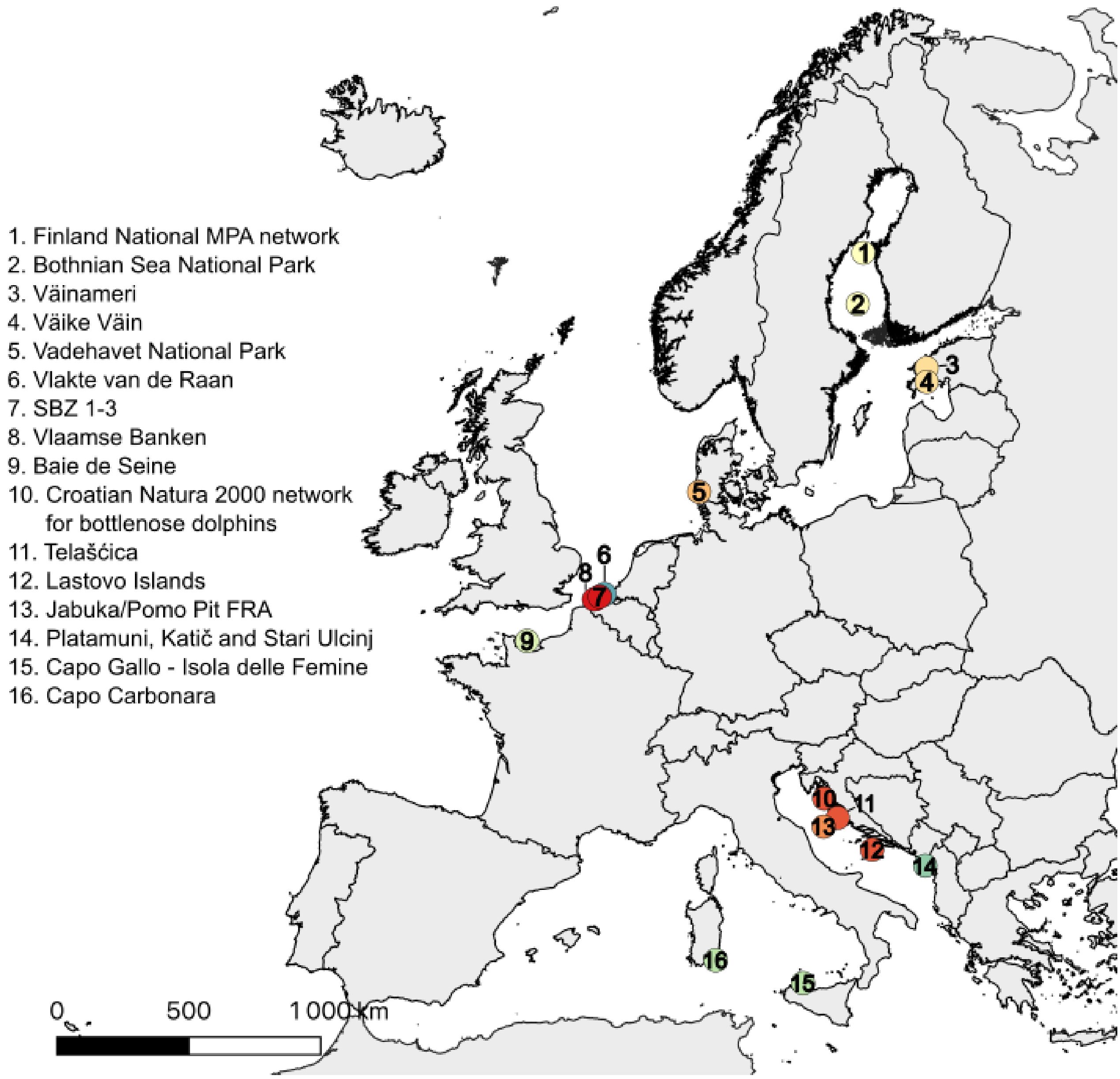

Figure 2. Locations of the Information Sites and Living Labs that provided grey literature for the gap analysis performed in Task 3.1.

3.2.2 Grey literature data extraction

Data were extracted from the grey literature by WP3 Project Partners, into a predefined extraction table. Data extracted focused on how ecological and environmental data support and are incorporated into MPA processes. This included summary information on the MPAs themselves including sea basin locations, associated countries, the type of MPA (single/network/part of a network), and the respective marine realm. Specific information about ecological and environmental data from each MPA included what ecological and environmental criteria (standards or principles for prioritizing, designating and managing conservation actions) were used, which indicators (specific measurements of biotic or abiotic components) are used to support associated

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criterion, and whether these are implemented or suggested by supporting documentation, and in which phase of the MPA they are used. Criteria and indicators were used in the frame of the deliverable as evidence of the ecological and environmental information effectively used or suggested in an MPA. We additionally asked for information on the types of knowledge used, their temporal resolution, temporal duration, spatial coverage, and any data incorporation strategy if applicable. Finally, we looked for details on monitoring of activities for management outcomes, and any relevant environmental or ecological assessment design.

3.3. Academic literature

3.3.1 Academic literature identification

A systematic review of academic literature was conducted to identify the state of the art relating to how ecological and environmental data is recommended to be used according to expert scientific advice. We focused our search efforts on academic literature presenting secondary evidence. Secondary evidence refers to the integration and/or re-analysis of the evidence generated in several previous studies (primary evidence) presenting the state-of-the-art or to provide new and generalizable insights in a topic. Secondary evidence resources include narrative reviews, systematic reviews with and without meta-analyses, letters and opinion papers/perspective papers. These sources were used as framing documents to outline the type of ecological and environmental information that should be considered in MPA processes according to the perspective of European and international experts, and to identify best practices for its effective incorporation into decision-making.

Between March – April 2024, academic literature representing secondary evidence was identified via Web of Science and Scopus using key words associated with MPAs ("marine protected area*" OR "protected area*" OR "marine protected area network*" OR "marine reserve*" OR "marine reserve network*" OR "marine park*" OR "marine park network*" OR "marine sanctuary*" OR "protected seascape*" OR "marine conservation area" OR "special area* of conservation" OR "other effective area-based conservation measures") AND ("ocean*" OR "sea" OR "marine" OR "brackish" OR "estuar*" OR "coast*" OR "benth*" OR "pelagic" OR "deep sea") AND ("plan*" OR "design*" OR "propos*" OR "commit*" OR "implement*" OR "develop*" OR "manage*" OR "establish*" OR "enforce*" OR "assess*"). This search string has been inspired, materialized and progressively refined based on the expertise of Project Partners and the preexisting search string used in the systematic review protocol with compatible scope published by Mangano et al., (2015).

Papers were screened following the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) protocol. Firstly, articles were identified via search strings in academic search engines and checked for duplication. Secondly, title and abstract level screening occurred with multiple reviewers confirming and agreeing to the articles screened. Thirdly, full-text screening was conducted, also with multiple reviewer validation. Lastly, data were extracted from the final

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selection of articles by a team of researchers. Please see Figure 3 for a comprehensive overview of the article screening process.

Articles were excluded for several reasons: 1) they did not discuss or explore how ecological or environmental data can be used to support MPA processes; 2) the article did not refer to MPAs or Other Effective Area-Based Conservation Measures (OECMs); 3) articles present specific primary evidence and are not secondary academic literature; 4) articles were not published in English.

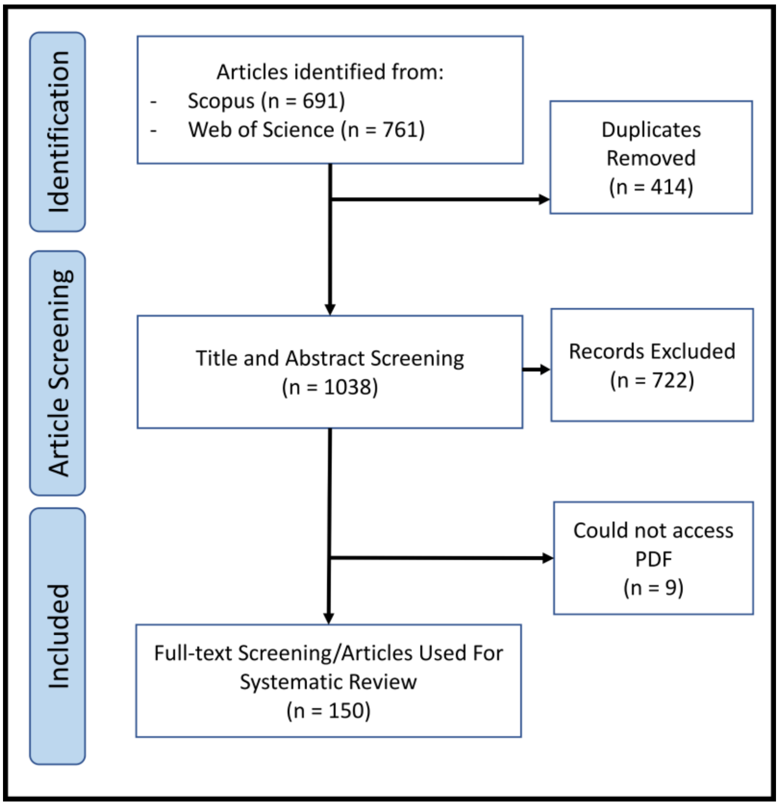

Figure 3. Flow diagram summarizing the systematic search and screening of academic secondary evidence followed in the deliverable.

3.3.2. Academic literature data extraction

Data were extracted from fully screened academic literature articles manually by researchers at University of Tartu and University College Dublin. Information extracted included bibliographic data about the article (title, publication year, authorship, DOI, type of article like systematic review or opinion piece, and publication focus). Specific information about how ecological and environmental data were or are recommended to be used according to the article included general knowledge topic about how standards and principles inform MPA processes (like biodiversity and connectivity), and knowledge subtopics associated to previously coupled indicators like species abundance. Additionally, we extracted data relating to the sources of ecological and environmental knowledge, which phase(s) of an MPA they relate to (as stated in the document or inferred based on the

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information provided by the authors), and associated keywords within the article. Finally, if an MPA was referenced in the document, we extracted information on whether the protected area was part of a network, which marine realms it covers, the level of protection offered, its geographic scope, name, sea basin, and country of operation.

3.4 Literature standardization

Once the grey and academic literatures were identified and compiled, we began a process allowing the direct comparison of disparate data sources. Knowledge and data on how ecological and environmental data has supported European MPAs both in terms of suggested approaches, and actual implementation had to be synchronized with the secondary academic literature identifying best practices. Three broad categories of knowledge and data to support MPA processes were identified; biotic (relating to factors directly resulting from living compartments), abiotic (physical and chemical features and processes), and human pressures (climate change and 4 human pressures categories from various human activities according to HELCOM, 2018). The classification used was inspired in the work done in D2.2 of the Horizon Europe project MSP4BIO (Withouck et al., 2023). These are summarized in Table 1. Categorizing the collected data in this manner allowed the comparisons of the grey and academic literature.

Table 1. Classification of data and knowledge used for MPA processes.

Criteria	Description
1. BIOTIC	
1.1 Ecological	
1.1.1 Functional/functioning	Criteria that describe species, community, and habitat properties and processes related to natural functioning, independent of anthropogenic pressures. This includes biotic processes and traits related to physiology, morphology, behavior, mortality, growth, breeding, and habitat functions such as breeding, foraging, spawning, and overall productivity.
1.1.1.1 Functional connectivity	Criteria that describe the functional connectivity of MPAs, encompassing biotic processes such as migration and other ecological interactions that facilitate the movement and exchange of organisms between areas.
1.1.2 Structural	Criteria that describe the structure, complexity, and ecological value of species, habitats, and ecosystems.
1.1.2.1 Structural connectivity	Criteria that describe the structural connectivity between habitats and migration corridors, emphasizing the physical linkages and spatial arrangements that enable movement.

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1.2 Genetic	Criteria that describe species and population's genetic structure, diversity, gene flows, inbreeding, and genetic connectivity.
2. ABIOTIC	
2.1 Oceanographic and hydrodynamic	Criteria that describe physical, chemical, and atmospheric changes, such as currents, nutrient dynamics, and freshwater input, that occur independently of anthropogenic pressures.
2.2 Geological and geomorphological	Criteria that describe seabed substrates, coastal structures, and other geological and geomorphological features that occur independently of anthropogenic pressures.
3. HUMAN PRESSURES	
3.1 Climate change related	Criteria related to climate change (e.g., adaptability, resilience, impacts).
3.2 Substance	Criteria that describe input of nutrients, organic matter, hazardous substances, litter, etc.
3.3 Energy	Criteria that describe energy input (e.g., heated water input from man-made facilities, sound disturbance, etc.).
3.4 Biological	Criteria that describe biological effects from invasive species, pathogens, genetically modified species, extraction of species, disturbance to species.
3.5 Physical	Criteria that describe physical disturbance to seabed, physical loss of seabed, changes to hydrological conditions

4. Gap analysis

4.1 Overview of the academic and grey literature

A total of 150 secondary academic documents matched our inclusion criteria. Most recommendations (n = 326) derived from the revised bibliography focused on the planning phase of MPAs (n = 133) followed by the site management, reviewing, and implementation phases. Most of the recommendations from scientific literature focused on considering biotic knowledge and data (82.5%) in the design and management of area-based conservation measures. Human pressures and abiotic aspects were considerably less highlighted in the revised bibliography, with only 15% and 2.5%, respectively (Figure 4A). The recommendations regarding abiotic factors are predominantly centered on oceanographic and hydrodynamic aspects, accounting for 87.5% of the focus, with a

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significant emphasis on biophysical modeling and oceanographic monitoring (Figure 4C). In terms of human pressures, there is a notable skew towards criteria associated with climate change, comprising 65.3% of the recommendations. This includes primarily designating Marine Protected Areas (MPAs) as climate refugia. Additionally, biological aspects related to human pressures, particularly fishing, constitute 16.3% of the focus. However, other aspects of human pressure are either minimally considered or entirely overlooked, with substance-related pressures at 6.1% and energy-related pressures at 0% (Figure 4D).

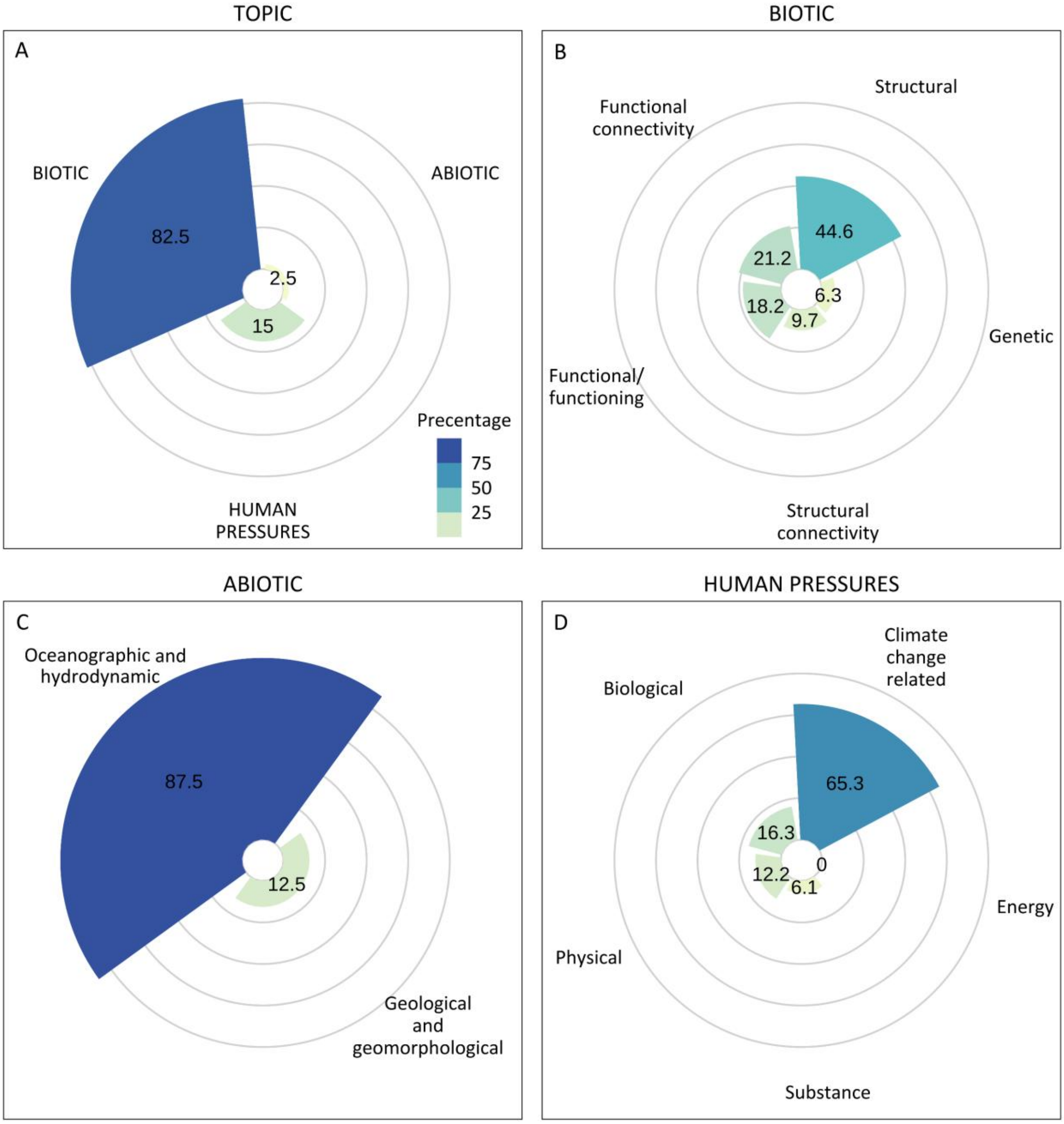

Figure 4. The representative proportions of different types of ecological and environmental knowledge recommended to be used in MPA processes identified in scientific literature.

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In the case of the grey literature, altogether 16 LL and IS gathered and extracted suitable information from documents framing the respective MPAs and defining management and monitoring plans (Figure 2). While Blue4all has 25 MPAs and MPA networks (12 IS and 13 LLs), not all provided suitable documentation for the purpose of this deliverable. Otranto Leuca, French Natura 2000 network - Channel North Sea, Torre Guaceto and the Irish MPA network expansion did not provide data to be extracted or did not have data that could be used from their baseline assessments. The Brazilian Parque Nacional Marinho de Fernando de Noronha was excluded to the focus on European MPAs for the purpose of this deliverable. Gyldensteen coastal lagoon, Baltic Sea MPA network, Marine Park of the Azores, Dundalk Bay did not provide information to the baseline assessment surveys.

A total of 143 documents were revised for this deliverable. The vast majority of implemented or suggested criteria were related to biotic dimensions (particularly structural and functional) across most of the phases of the analyzed MPA processes as was the case for academic literature. Over half of the European MPAs considered both structural (75%) and functional (58%) components in the reviewing phases (Figure 5). A significantly lower percentage of the MPAs have already considered those components in the initial phases of the MPA process. In the planning phase, the significantly lower number of MPAs may be attributed to the limited availability of documentation from the early stages of the process. Structural and functional connectivity were largely overlooked in all phases of the MPA processes, with a maximum of only 8% of the MPAs considering these aspects. Abiotic dimensions and human pressures were considered in less than half of the MPAs, except for geological and geomorphological aspects extensively considered through the mapping and prioritization of non-biogenic habitats (Figure 5).

The amount and variety of ecological and environmental aspects considered in MPA processes varies between European MPAs with some considering all potential aspects and some only a few (Figure 6). Vadehavet National Park in Denmark and Vlakte van de Raan in the Netherlands are considering most of the potential criteria suggested by scientific literature and are representing well-planned and managed MPAs. However, most European MPAs are only considering a few of the needed ecological and environmental components relevant to the area, indicating potential problems in the efficiency of the established MPAs.

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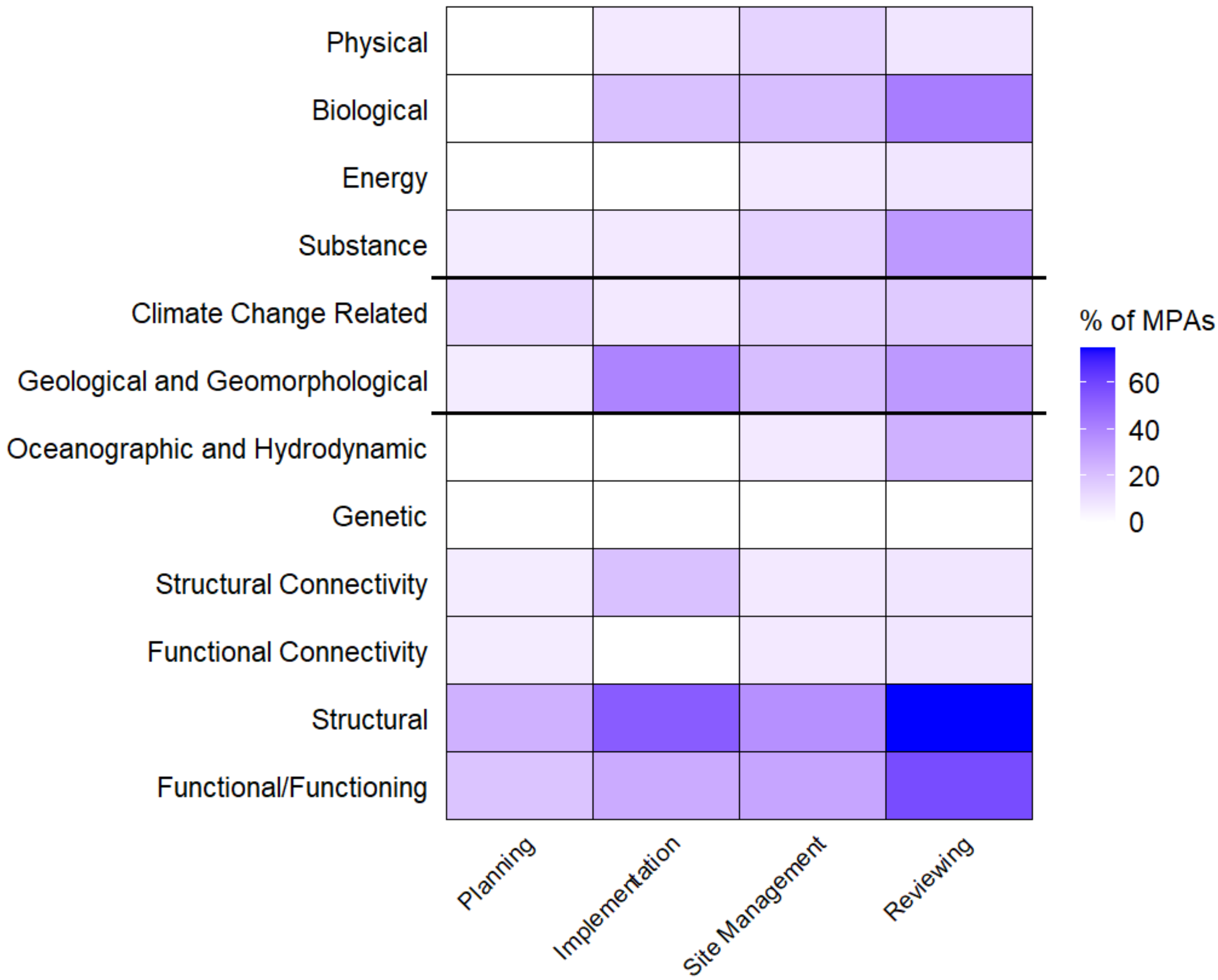

Figure 5. The proportions of MPAs where different ecological and environmental criteria have been suggested or implemented in different phases of the European MPA processes.

4.2 Biotic information

4.2.1 Structural and functional dimensions

Regarding the biotic topic, most of the academic literature recommendations were related to structural aspects (i.e., species and biogenic habitats) of marine ecosystems, with a progressive increase over the last decade of the consideration of functional aspects (i.e., the life history and ecological role of species) and ecosystem functioning (i.e., the processes that define the way in which energy flows and matter is cycle in ecosystems) in the specialized bibliography looking at improving the way in which ecological knowledge is mainstream into the design and management of area-based conservation measures (Figure 4B). This trend follows the theoretical and empirical efforts of the last three decades looking at understanding how biodiversity and its changes shape the way in which ecosystems function and respond to Global Change drivers, and ultimately affect nature contributions to people (e.g., Chapin III et al., 2000; Loreau et al., 2001; Cardinale et al., 2012;

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Tilman et al., 2014; Ali 2023). Lessons derived from ecological research such as the need to put a particular emphasis on the functional traits and role of species over their taxonomic identity (Díaz et al. 2006) or the pivotal relevance that functional diversity and redundancy play in defining the magnitude and stability of ecosystem functioning (Eisenhauer et al., 2023), have started to be recognized and effectively implemented in the conservation bibliography (e.g., Miatta et al., 2021).

In the analyzed European MPAs structural aspects have been universally considered (Figure 6), most probably due to the overall low technical demands for its use, the generally large data availability for its implementation related to is relatively simple and inexpensive monitoring, and their more “tangible” and easy to interpret nature. Over 80% of the MPAs are also considering functional aspects, apparently following the trend described in academic literature. However, even when these aspects are considered, the focus is placed on the prioritization of areas where organisms develop part of the life cycles or particular activities (e.g., feeding, resting, breeding) rather than on the actual measurement of ecosystem processes (e.g., carbon storage and sequestration, nutrient cycling, productivity), their spatial distribution or the relative contribution of different species to them. In contrast to what we have previously described about structural aspects, the consideration of the forementioned functional aspects might have been prevented in MPA processes by the need of sophisticated experimental and field methods for their estimation , the need for not always available proxies for the marine environments (e.g., species functional traits) and the difficulties to interpret and communicate their meaning in the context of conservation and management.

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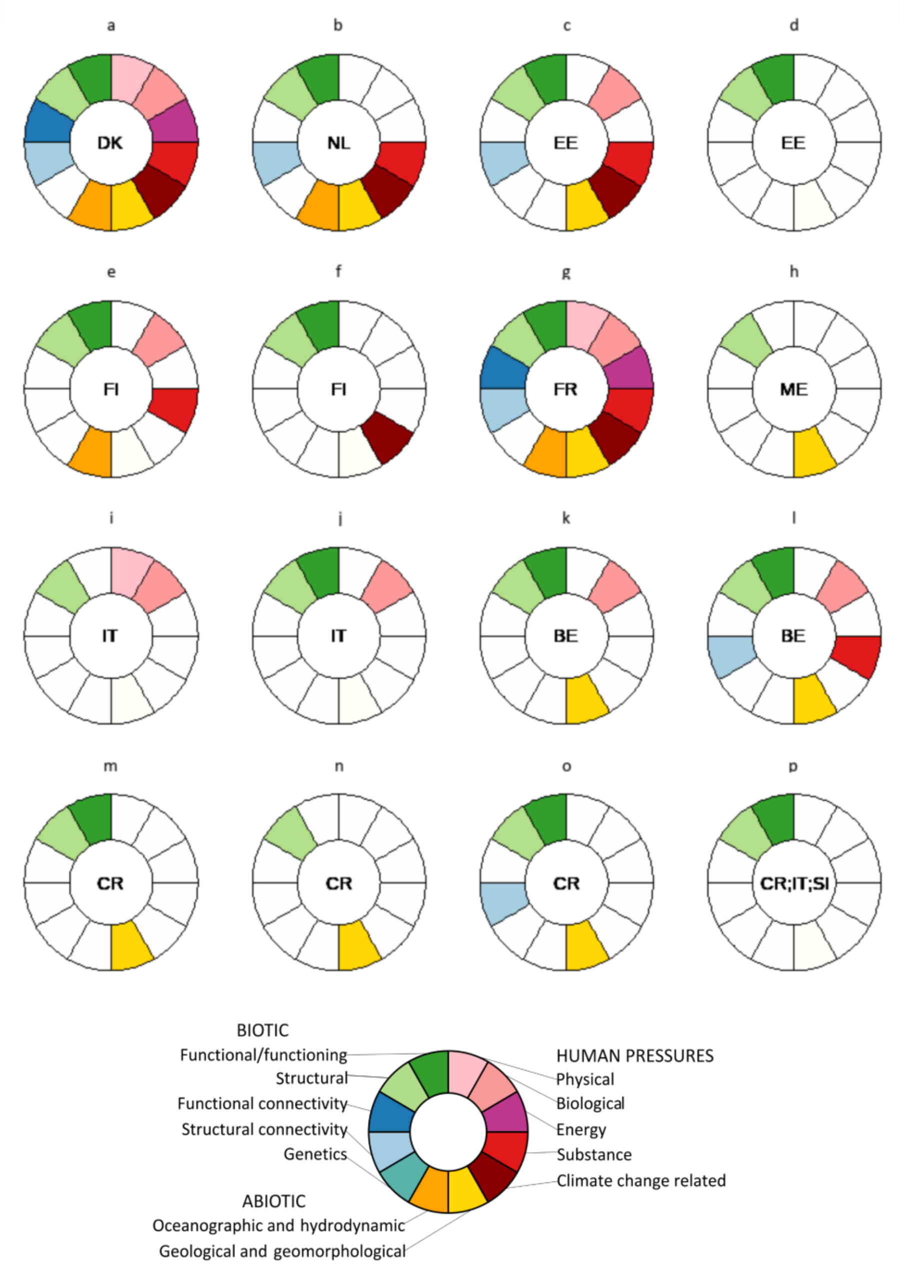

Figure 6. Ecological and environmental criteria have been suggested or implemented in MPA processes for 16 European MPAs - a) Vadehavet National Park, b) Vlakte van de Raan, c) Väinameri, d) Väike Väin, e) Bothnian Sea National Park, f) Finland National MPA network, g) Baie de Seine, h) Platamuni, Katič and Stari Ulcinj, i) Capo Gallo - Isola delle Femine, j) Capo Carbonara, k) Vlaamse Banken, l) SBZ 1-3, m) Lastovo, n) Telašćica, o) Croatian Natura 2000 network for bottlenose dolphins , p) Jabuka/Pomo Pit FRA.

4.2.2 Connectivity

The importance of considering connectivity in MPAs processes is well-documented in the scientific literature (e.g., Balbar and Metaxas, 2019; Beger et al., 2022; Darnaude et al., 2024). Despite the

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recognized role that both structural and functional connectivity play in shaping the structure and functioning of ecosystems and their overall resistances and resilience to stress (O'Leary et al., 2018; Darnaude et al., 2024; Figure 4B), in practice, analyzed European MPAs processes have generally not substantially considered and integrated connectivity (Figure 5, 6). The considered MPAs provide a clear overview of how the overall design and management of area-conservation measures across Europe has generally remained spatially restrictive focusing only on local biological components and overlooking their movement and dependencies beyond the boundaries the defined area.

When connectivity has been meaningfully considered (mostly during the planning and reviewing phases, Figure 5) and properly documented (in only 5 out of 16 of the MPAs, Figure 6), structural connectivity has been the main and, in most cases, single form of connectivity included. The design and management of European MPAs have predominantly focused on structural connectivity, considering aspects such as migration corridors and habitat continuity. This bias towards structural connectivity arises due to its overall easier implementation through the generally available data on habitats distribution. In contrast, quantifying or inferring functional connectivity demands the generation of highly technical information using chemical tags, genetic markers, tracking technologies and/or advanced hydrodynamic models, preventing its effective implementation in the design and management of MPAs and MPA networks. In the case of European MPA networks, where connectivity has a superlative role in defining the spatial arrangement and assessing the spatial coherence of protected areas, the consideration of structural connectivity or functional connectivity surrogates (*sensu* Balbar and Metaxas, 2019) prevails. For example, proxies derived from the combination of species and habitat distribution data with available bibliographic or expert-based estimations of maximum dispersal and information on reproductive strategies have been used to theoretically assess functional connectivity (see HELCOM, 2016 for an implementation in an ecological coherence assessment of the Baltic Sea MPA network).

4.2.3 Genetics

The consideration of genetic aspects (e.g. genetic diversity, genetic population structure, gene flows, inbreeding, genetic connectivity) in MPA processes is recommended in scientific literature less than other biotic aspects (6.3%), despite its significant role in maintaining biodiversity, ecosystem health, and resilience (Beger et al., 2022, Baco et al., 2016, Marti-Puig et al., 2013, Figure 4B). However, genetic aspects have not yet been effectively incorporated into the management and design of the analyzed European MPAs (Figure 5). This omission is concerning because genetic aspects ensure the exchange of genetic material between populations, which is vital for species' adaptation to changing environmental conditions, reducing the risk of inbreeding, and enhancing overall population viability. Integrating genetic aspects into MPA planning would enable more robust conservation strategies that support the long-term sustainability and evolutionary potential of marine species, thereby strengthening the ecological networks that sustain marine biodiversity.

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4.3 Abiotic

Scientific literature largely overlooks abiotic aspects (2.5%) in the context of MPAs (Figure 4A). When considered, recommendations mainly focus on oceanographic and hydrodynamic aspects (Figure 4C). In contrast, European MPAs mainly consider geological and geomorphological aspects (Figure 5). Indicators related to sediment and geomorphological criteria, such as caves, sandbanks, and reefs, are relatively stable and easier to monitor and quantify (Cooper et al., 2019, Kenny et al., 2003). On the other hand, hydrodynamic components are highly dynamic, requiring long-term data collection and an understanding of natural fluctuations over various timescales, which poses significant challenges (Jahanmard et al., 2022). The knowledge of oceanographic conditions is essential for measuring connectivity indicators (Boteler et al., 2022) and the current lack of considering these hydrodynamic and oceanographic aspects hampers the effective incorporation of functional connectivity into MPA processes. This gap in knowledge complicates efforts to design and manage MPAs that fully account for the complex interactions between biological and physical factors, ultimately undermining the effectiveness of conservation strategies aimed at preserving marine biodiversity and ecosystem health.

4.4 Human pressures

In academic literature, considering human pressures in MPA processes is recommended (15%, Figure 4A), with a strong focus on climate change related aspects (Figure 4D). However, only 56% of the European MPAs consider how human pressures affect area-based conservation measures, both under current and future scenarios. When human pressures are considered, the majority focus on biological pressures (43%) (e.g., fishing pressure, invasive species) and substance-related pressures (31%) (e.g. pollution), which contradicts recommendations from scientific bibliography (Figure 4D, 5). The low consideration of other anthropogenic stressors, including climate change affects, coastal development, energy input, and physical disturbance of habitats and species, could have profound and cumulative impacts on MPA sustainability and effectiveness (Simeoni et al., 2023, Kennish 2022).

To address these issues comprehensively in MPA processes, Decision Support Tools (DSTs) can be invaluable. DSTs help assess and integrate single and multiple human pressures, providing a more holistic approach to MPA management. These tools can model and predict the impacts of various activities, assess the effectiveness of management measures, and guide decision-makers in implementing adaptive strategies. By using DSTs, managers can better anticipate future changes, balance competing uses, and enhance the resilience of MPAs to both current and emerging threats, ultimately ensuring the long-term protection and sustainability of marine environments.

4.5 Type of knowledge

Almost all the recommendations on data types looking to support MPA processes were categorized as scientific data (either derived from actual research or expert-based knowledge). Although the

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assessed European MPAs have stated in the BLUE4ALL baseline survey that over 80% have used local and traditional knowledge in MPA processes, it is poorly documented and only 3 of the 16 MPAs included in this study provided information on how this has been practically implemented. Similarly expert assessment is stated to be used in MPA processes for over 90% of the investigated MPAs but in only 7 of the 16 MPAs this has been documented.

5. Operationalization of novel knowledge and concepts

Based on our findings and gap analysis, this section provides a series of recommendations on how to operationalize novel knowledge and data for MPA design and management. We discuss four key sections identified through the gap analysis outlined in Section 4. These are ensuring that the design and management of MPAs is spatially comprehensive, the temporal adaptability of MPAs, using key groupings of indicators for MPA processes, their structural and functional aspects, and the need to better factor in local knowledge to MPA decision making.

5.1 Data collection and monitoring for marine protected areas processes

The examination of grey literature highlights that data collection and monitoring practices for European MPAs are notably inconsistent. A key theme from the whole grey literature dataset is many outlined ecological and environmental criterions do not have specific types of knowledge, temporal durations, temporal resolutions, or spatial coverage associated with them. This inconsistency poses significant challenges for the effective design and management of MPAs across Europe. To address these challenges, it is crucial to establish comprehensive and systematic data collection and monitoring protocols that can provide reliable and continuous information on the state of MPAs.

5.1.1 Establishing baselines

A thorough baseline of ecological and environmental data is essential before designating an MPA. This baseline should include comprehensive species inventories, detailed habitat maps, accurate water quality metrics, and prevailing environmental conditions including anthropogenic pressures (Hopkins et al., 2016; Grorud-Colvert et al., 2021). But also identifying gaps in understanding by noting which kinds of data are absent about the marine ecosystem in question. By establishing such a baseline, practitioners and policymakers can have a clear understanding of the existing conditions and identify areas that require protection (Pressey et al., 2015). It is important to highlight that debate exists around how far back in time a baseline should be, and what targets it should help set. Additionally, historical data, where available, should be utilized to supplement understanding of long-term changes and establish trends (Bean et al., 2017). Historical data can provide insights into the natural variability and anthropogenic impacts on marine ecosystems, helping to inform future conservation efforts (Thurstan et al., 2017). This is particularly relevant when designing MPAs around the impacts of climate change.

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However, data from the grey literature reveals that long-term datasets are often inconsistent and fragmented. This lack of coherent and continuous data makes it challenging to draw accurate conclusions about ecological trends and the effectiveness of MPAs. Therefore, there is a pressing need for standardized data collection methodologies and long-term monitoring programs to ensure that data is comparable over time and across different MPAs.

5.1.2 Regular and consistent monitoring programs

Implementing regular monitoring programs is critical for tracking changes in species abundance, biodiversity, habitat condition, and other ecological indicators within and the surroundings of the MPAs (Nagendra et al., 2013). Such programs should be designed to collect data at consistent intervals, using standardized methods to allow for comparison over time, and potentially compare other MPAs, particularly when establishing an MPA network (Edgar et al., 2014). Regular monitoring can help detect early signs of ecological degradation or recovery, enabling timely management interventions. Regular monitoring can also have secondary benefits like supporting scientific research and contributing to understanding long-term regional and sea basin ecological and environmental trends (Kleitou et al., 2021; Bianchi et al., 2022).

Monitoring programs should encompass a variety of ecological indicators, including species diversity, population abundance, habitat integrity, water quality parameters, and anthropogenic activities and pressures (Hayes et al., 2019; Addison et al., 2015). For instance, regular surveys of key species, such as indicator species or those of conservation concern, can provide valuable information on the health of marine ecosystems. Key species could also extend to functionally relevant species which are important biological components to maintain the functioning of MPAs. Monitoring programs should also survey anthropogenic impacts, if possible, like fisheries impacts, bycatch, pollution, and climate change (Perera-Valderrama et al., 2020; Noble-James et al., 2023). Monitoring programs both inside and outside of MPAs would be ideal to better understand the pressures protected areas are subjected to. By monitoring biotic, abiotic, and anthropogenic components of marine ecosystems and MPAs, it becomes possible to generate a comprehensive understanding of the ecosystem. This allows managers, policy makers, and other practitioners to appropriately respond and plan to current and potential changes to the marine ecosystem and MPA (Hoppit et al., 2022). Monitoring programs are critical to current and future MPA management, and despite financial pressures these programs should not be cut but rather expanded given their importance to marine ecosystems.

5.1.3 Addressing fragmentation and inconsistency with data monitoring

To address the inconsistencies and fragmentation of long-term datasets, it is essential to develop and implement standardized protocols for data collection and monitoring across all MPAs (Pelletier 2020). This standardization can facilitate data comparability and integration, enabling more accurate assessments of ecological trends and the effectiveness of conservation measures. Collaborative efforts among researchers, governments, NGOs, and international organizations are

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necessary to establish and maintain these standardized protocols (Bianchi et al., 2022; Edgar et al., 2014).

Also, creating centralized databases where monitoring data can be stored, accessed, and analyzed can improve data management and utilization. These databases should be designed to accommodate data from various sources, including grey literature, and ensure that data is easily accessible to all stakeholders involved in MPA design and management. Developing and adhering to standardized protocols for data collection, storage, and sharing to ensure consistency and comparability. Lastly, by making data publicly accessible where possible to facilitate transparency and broader scientific use.

5.1.4 Using systematic review and European data infrastructure

When local data for a specific MPA or sea-basin is unavailable, systematic reviews can be a powerful method to collect and synthesize scientific data from broader geographic regions, in situations where detailed habitat mapping is unavailable. Systematic reviews involve a comprehensive and structured approach to gathering, evaluating, and synthesizing existing research and data. By collating information from multiple studies and reports, researchers can obtain a more holistic understanding of marine ecosystems, including trends, impacts, and patterns that transcend the boundaries of individual MPAs or sea-basins.

In addition to systematic reviews, the use of European Data Infrastructure such as Copernicus and the European Marine Observation and Data Network (EMODnet) can significantly enhance the collection of marine data. Copernicus, the European Union's Earth observation program, provides comprehensive data from satellite and in-situ observations. This data includes information on oceanographic parameters such as sea surface temperature, chlorophyll concentration, and sea level, which are crucial for understanding marine environments. EMODnet, on the other hand, offers a wide array of marine data, ranging from bathymetry and geology to biology and human activities. By integrating data from these sources, researchers can obtain a completer and more accurate picture of marine conditions and processes.

Using these European Data Infrastructures allows for the collection and analysis of high-resolution, up-to-date data essential for marine conservation and management. Copernicus and EMODnet provide standardized, interoperable datasets that can be easily accessed and used for various applications, including environmental monitoring, spatial planning, and policymaking. By combining systematic reviews with data from Copernicus and EMODnet, researchers can overcome the limitations of local data scarcity and make informed decisions to protect marine biodiversity and sustain marine resources. This integrated approach ensures that conservation efforts are based on the best available science, enhancing their effectiveness and resilience in the face of environmental challenges.

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5.2 Ensuring marine protected areas are spatially comprehensive

5.2.1 Incorporate ecological connectivity into marine protected areas design

European MPAs can be designed to be spatially comprehensive by incorporating ecological connectivity, which ensures the movement and interaction of species across different habitats and ecosystems. Ecological connectivity is essential for maintaining biodiversity, enhancing the resilience of marine species to environmental changes, and supporting healthy ecosystem functions. To achieve this, MPAs should be designed with an understanding of the spatial and temporal dynamics of marine life, encompassing various ecological processes and habitat requirements.

Connectivity has many branching concepts. There is passive connectivity which relates to oceanographic processes and relates to features like ocean currents, and nutrient upwellings (Pitcher et al., 2010). Active connectivity, otherwise termed migratory connectivity, whereby organisms transition from one area to another such as the movement of marine mammals seasonally to feed (Berkström et al., 2022). Habitat connectivity, the linkage of different patches of similar habitat (Olds et al., 2012). And seascape connectivity, connection between various habitat types (Selkoe et al., 2016).

Connectivity is often associated with networks of MPAs (Balbar and Metaxas, 2019). There are challenges with incorporating connectivity in network design. Determining connectivity can be very resource intensive, requiring significant investment in scientific expertise and monitoring (Li and Fluharty, 2017). For example, determining genetic connectivity to understand population dynamics may require extensive sampling and analysis time to reach definitive understandings (Sahyoun et al., 2016). This can also be costly, and outside of the scope of MPA operational procedure to conduct. Bias can also exist in the focus of species and habitats that knowledge exists for, like charismatic species such as birds. But for more complete understandings of marine ecosystems to benefit MPAs there needs to be understandings of foundational features key to ecosystem functionality like primary producers (Fletcher et al., 2011).

One key approach is to include habitat corridors within MPA networks. Habitat corridors are stretches of protected areas that link larger MPAs, allowing species to move freely between them (Pendoley et al., 2014). These corridors are particularly important for species with large home ranges, migratory species, and those that require different habitats at different life stages. By protecting these movement pathways, MPAs can support genetic diversity and population stability, reducing the risk of local extinctions and promoting resilience against environmental stressors.

In addition to corridors, the concept of "steppingstones" can be utilized. Steppingstones are smaller, strategically placed protected areas that serve as intermediate habitats for species migrating between larger MPAs (Balbar and Metaxas, 2019). These areas provide essential stopover points for rest, feeding, and breeding, especially for species that undertake long-distance migrations. For instance, fish that migrate between spawning and feeding grounds or sea turtles that travel vast

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distances can benefit from such steppingstone MPAs, ensuring their life cycle processes are uninterrupted.

5.2.2 Use multi-scale connectivity

To ensure these MPAs are effective, it is essential to consider multi-scale connectivity, which involves understanding and integrating ecological processes and species movements across various spatial and temporal scales. Multi-scale connectivity enhances the spatial comprehensiveness of MPAs, ensuring that they protect ecological functions and services effectively (Roberts et al., 2021; Christie et al., 2010).

On the local scale, connectivity within individual MPAs ensures that habitats are contiguous or closely linked, allowing species to move freely for feeding, breeding, and shelter (Balbar and Metaxas, 2019). For example, algal and seagrass beds often provide interconnected habitats essential for the life cycles of many marine species. By maintaining connectivity among these habitats within an MPA, managers can support the local population dynamics and resilience of marine species (Carr et al., 2017). This intraregional connectivity is crucial for the survival of species that rely on multiple habitats during different life stages.

On a broader scale, regional connectivity between MPAs allows for the movement of species across larger geographical areas, which is vital for the maintenance of genetic diversity and the replenishment of populations (Friesen et al., 2019). Many marine species undertake long-distance migrations for spawning, feeding, or as part of their life cycle, such as sea turtles and certain fish species. By creating networks of MPAs that are ecologically connected, conservation efforts can support these migratory routes and facilitate the flow of genetic material between populations (Carr et al., 2017). This regional connectivity also helps mitigate the impacts of localized disturbances, such as pollution or climate change effects, by providing alternative habitats and ensuring population stability across the network (Botsford et al., 2009).

Considering connectivity at the ecosystem scale involves understanding and preserving the linkages between different ecosystems that are crucial for the overall health of the marine environment (Sheaves 2009). For instance, the interaction between coastal and offshore ecosystems, such as the nutrient flow from rivers to estuaries and subsequently to open ocean areas, is vital for maintaining productivity and biodiversity. Integrating these ecosystem-level connections into MPA design helps in preserving essential ecological processes that support the broader marine environment (Barr 2013).

5.2.3 Methods for estimating connectivity

One method for estimating connectivity is using demographic approaches to measuring connectivity involve individual-based modeling that produces dispersal trajectories, connectivity matrices, and dispersal kernels (Day et al., 2020; Treml et al., 2008). These methods have been widely employed to understand the movement and settlement patterns of marine species. Studies often adapt metrics to the specific life history traits of different taxa and combine them in multi-species analyses

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(D'Aloia et al., 2017). For example, electronic and natural passive tagging have been used to measure connectivity, with electronic tags particularly effective for tracking the movements of large predators within and between MPAs. Natural or artificial markers help delineate the natal origins of various life stages of marine organisms in MPAs. These demographic methods can inform the design and management of MPAs by identifying critical steppingstones, sources, retention zones, and spillover areas, thereby enhancing the effectiveness of conservation efforts (Balbar and Metaxas, 2019).

Another way to estimate connectivity is via seascape approaches which utilize habitat modeling to infer connectivity in scenarios where direct data on spatial distribution are limited (Grober-Dunsmore et al., 2009). These methods assess habitat linkages, ecological coherence, and seascape surrogates such as reproductive output patterns. For instance, ecological coherence analyses in the Baltic Sea have been used to evaluate the connectivity of existing MPAs (Berkström et al., 2022). Seascape measures can also provide insights into larval subsidies and habitat protection benefits when empirical data are sparse. Management plans often integrate these approaches to connect offshore MPAs with coastal marine parks, ensuring broader habitat connectivity (Carr et al., 2017). Such integration is vital for maintaining ecological processes and species movements across large marine landscapes, enhancing the overall resilience and functionality of MPA networks.

The last main category for estimating connectivity is with genetic methods, offering detailed insights into gene flow, population structure, and haplotype diversity (Sahyoun et al., 2016; Xuereb et al., 2020). These approaches are useful in both the design of new MPAs and post hoc analyses of existing ones. Genetic metrics can reveal patterns of isolation by distance and inform the placement of MPAs to promote genetic connectivity. For example, populations with fine-scale genetic structure may benefit from closely spaced MPAs that act as genetic steppingstones (Jenkins and Stevens, 2018). Although genetic approaches are less frequently discussed in management literature, they are crucial for understanding and preserving the genetic diversity of marine populations, which is essential for long-term species survival and adaptability.

When direct quantitative measures of connectivity are not feasible, surrogate measures can be used. These include rules of thumb based on ecological and environmental characteristics such as planktonic larval duration and current patterns (Roberts et al., 2003). While these surrogates provide useful guidelines for MPA size and spacing, they are less reliable than empirical methods and may not capture species-specific connectivity patterns. Therefore, post-hoc assessments are necessary to evaluate the effectiveness of MPAs designed using these surrogates (Balbar and Metaxas, 2019). Practitioners should be cautious when applying these guidelines across different ecosystems, as they may not be universally applicable.

Each method for measuring connectivity has its limitations, making it essential to use a combination of approaches for a robust assessment. For example, biophysical models have computational constraints (Swearer et al., 2019), genetic methods assume specific population conditions (Willi et al., 2022), and tagging is often limited to larger species. Cross-validating results from multiple

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methods can provide a more comprehensive understanding of connectivity patterns. Combining demographic, seascape, genetic, and surrogate measures allow for a holistic view of marine connectivity, improving the design and management of MPAs (Riginos and Beger, 2022). This integrated approach ensures that MPAs are effective in their goals.

5.2.4 How to mainstream connectivity into marine protected area design and management

Balbar and Metaxas (2019), in their review paper, recommend a framework for better adding connectivity in marine protected area design and management. To effectively incorporate connectivity into the design and management of MPAs, it is essential first to identify clear conservation objectives. These objectives often focus on the protection of specific habitats, such as biogenic, unique, or pristine areas, or on species, including their spawning, foraging, and nursery grounds. Practitioners and scientists must collaborate to determine which objectives should consider connectivity. This collaboration ensures that connectivity is appropriately factored into MPA design, aligning with the broader ecological goals of the protected areas.

Once conservation objectives and target areas are established, scientists can focus on collecting data to calculate relevant connectivity metrics (Daigle et al., 2020). These metrics might include larval output, dispersal patterns, and home range sizes for source populations or centrality metrics for steppingstone functions within MPA networks. Data collection should encompass biological, physical, and geological variables, derived from surveys and empirical measurements. Tools like tagging, tissue sampling, and ocean circulation models help generate comprehensive connectivity matrices and network theory metrics, which are crucial for informed MPA design.

Interpreting connectivity data accurately is crucial for its practical application in MPA design (Jonsson et al., 2020). Scientists must translate connectivity outputs, such as dispersal distances and connectivity matrices, into actionable metrics for managers. For instance, dispersal distances inform the optimal size and spacing of MPAs to ensure effective self-recruitment or inter-MPA dispersal (Berkström et al., 2022). Connectivity matrices provide detailed information on the origins and destinations of populations, guiding the placement of MPAs to enhance network connectivity.

Continuous evaluation of MPA connectivity is vital to assess their effectiveness, particularly in the context of climate change and incremental MPA designations (Van Diggelen et al., 2022). Scientists should use the same methods employed during the design phase to conduct post-hoc evaluations, ensuring MPAs meet their connectivity-related conservation objectives. Recommendations for improving MPA networks may include adding new areas, adjusting boundaries, or modifying zoning (Horta e Costa et al., 2022). Effective communication between scientists and managers is crucial to implementing these recommendations and adapting MPAs to enhance their connectivity and overall ecological function.

5.2.5 Use systematic conservation planning

Systematic conservation planning is a structured approach to identifying and implementing conservation actions that achieve biodiversity protection goals efficiently and effectively (Tetley et

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al., 2022). When applied to marine environments, it becomes an invaluable tool for designing MPAs that are both spatially comprehensive and ecologically coherent. This planning method involves a series of steps that include setting clear conservation objectives, gathering spatial data on biodiversity and human activities, and using advanced spatial analysis to identify priority areas for conservation.

A critical aspect of systematic conservation planning is its focus on achieving representativeness and comprehensiveness within MPAs. Representativeness ensures that all biodiversity features, including species, habitats, and ecosystems, are included within the protected areas. Comprehensiveness aims to protect a full range of biodiversity within the network of MPAs, ensuring that various ecological processes and functions are maintained. By utilizing systematic conservation planning, decision-makers can create a network of MPAs that collectively cover the diversity of marine life and habitats, thus safeguarding the ecological integrity of marine ecosystems.

One of the key benefits of systematic conservation planning in marine conservation is its ability to incorporate both biotic, abiotic, and anthropogenic data into the planning process (Kuismanen et al., 2023). This includes information on species distributions, habitat types, and ecological connectivity, as well as data on human activities such as fishing, tourism, and shipping. By integrating these diverse datasets, systematic conservation planning helps to identify areas where conservation efforts will be most effective, minimizing conflicts with human uses and maximizing ecological benefits. This data-driven approach allows for the creation of MPAs that not only protect biodiversity but also support sustainable use of marine resources.

5.2.6 Incorporate adaptive management

Incorporating adaptive management into European MPA processes is essential to ensure they remain spatially comprehensive in the face of dynamic environmental changes, and is an approach increasingly advocated within academic literature (Woods et al., 2022; Katsanevakis et al., 2020). Adaptive management is a structured, iterative process with practitioners of robust decision-making in the face of uncertainty, with an emphasis on learning and adapting. It focuses on continually learning and understanding the management system in question and is not considered an end goal but a continual process to be constantly engaged. This approach is pertinent for MPAs, as it allows for the continuous assessment and adjustment of management strategies in response to new scientific information and changing ecological conditions.

One of the core elements of adaptive management in MPAs is the establishment of comprehensive monitoring programs (Uychiaoco et al., 2005). These programs systematically collect data on various ecological and environmental parameters, such as species populations, habitat conditions, and water quality (Dunham et al., 2020). By analyzing these data, managers can detect trends and changes that may indicate the need for modifications in MPA boundaries or management practices. For example, if monitoring reveals a decline in a key species within an MPA, managers can

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investigate the causes and implement targeted conservation measures, such as habitat restoration or fishing restrictions, to address the issue.

Operationalizing ecological and environmental data into MPA processes involves several critical steps. First, it is essential to develop robust data collection methodologies that ensure consistent and reliable monitoring (Noble-James et al., 2023). This might involve the use of remote sensing technologies, gathering previous scientific knowledge, and citizen science initiatives to gather comprehensive data across various spatial and temporal scales. Integrating data from diverse sources helps to create a more accurate and holistic understanding of marine ecosystems, enabling better-informed management decisions.

Second, the data collected must be systematically analyzed using statistical and modeling tools. These tools can help identify patterns, trends, and potential causal relationships within the data. For example, spatial analysis techniques can be used to map species distributions and habitat conditions, while predictive models can forecast the impacts of different management actions or environmental changes. By leveraging these analytical tools, managers can gain insights into the underlying drivers of ecological changes and the likely outcomes of various management strategies.

Third, the insights gained from data analysis must be effectively communicated to decision-makers and stakeholders (Parnell and Bresnick, 2013). This involves translating complex scientific findings into actionable recommendations that can inform management decisions. Decision support systems and interactive visualization tools can be used to present data in an accessible and intuitive format, facilitating informed discussions and collaborative decision-making. Engaging stakeholders in the interpretation and application of data ensures that management actions are grounded in both scientific evidence and local knowledge, enhancing their relevance and acceptability.

Finally, adaptive management requires a feedback loop that incorporates the outcomes of management actions into the ongoing cycle of monitoring and decision-making (Williams 2011). This iterative process allows for continuous learning and improvement, as managers can assess the effectiveness of implemented measures and adjust strategies based on observed outcomes. For instance, if a particular conservation measure proves ineffective, managers can refine or change their approach based on new data and insights. This dynamic and responsive approach ensures that MPAs remain adaptable to changing conditions and can achieve their conservation objectives in the long term.

5.2.7 Climate change and other human pressure considerations

Climate change impacts, such as rising sea temperatures, ocean acidification, changes in salinity, deoxygenation, and sea-level rise, significantly alter marine habitats and biodiversity patterns (Kroeker et al., 2013; Hu et al., 2022). Changes in the contextual ecological and environmental features risk undermining current MPA strategies and management approaches (Hoppit et al.,

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2022). Therefore, MPAs must be designed and managed to account for these dynamic changes to effectively conserve marine ecosystems. Current reporting on MPA processes should be expanded to consider climate change impacts.

One key consideration is the inclusion of climate refugia—areas less affected by climate change that can provide stable conditions for species under stress (Wilson et al., 2020). By identifying and protecting these refugia, MPAs can offer safe havens for species and ecosystems, helping to maintain biodiversity and ecological functions. Additionally, it is crucial to consider species' functional traits in response to climate change, as these traits significantly condition the well-being of species (Albouy et al., 2020). These traits include physiological tolerance to temperature and salinity, reproductive strategies, and feeding behaviors. By incorporating an understanding of functional traits into the design and management of MPAs, we can better anticipate and mitigate the impacts of climate change on marine life.

Connectivity between MPAs is another vital aspect (O'Regan et al., 2021; Brooks et al., 2020). As species migrate in response to shifting temperatures and habitat changes, interconnected networks of protected areas can facilitate their movement, ensuring genetic flow and reducing the risk of local extinctions. MPAs should be strategically located to create corridors that link critical habitats, such as spawning grounds, feeding areas, and migration routes (Allan et al., 2021). This approach enhances the adaptive capacity of marine species and ecosystems, allowing them to respond more effectively to climate-induced changes. It is important to note that connectivity as an adaptation and mitigation measure for climate change has limitations (Schmidt et al., 2022). For example, organisms generally move northwards following their climactic envelope. However, in sea basins like the Mediterranean and the Baltic which are semi enclosed, eventually moving further northwards is no longer possible. Therefore, it is important to also recognize the potential limitations that trying to operationalize MPA connectivity in response to climate change.

Another key factor is organism and habitat migration to climate change may not happen at commensurate rates (Early and Sax, 2011). Resulting in shifts in ecosystems, and potentially creation novel ones. The environmental, ecological, and legal basis for many European MPAs stems from the species and habitats of conservation concern used to establish them (Grorud-Colvert et al., 2021). These originate from the Birds and Habitats Directives. It is unclear what will happen to MPAs if or when their foundational conservation features suffer climate induced migrations, leaving the protected areas behind (Hoppit et al., 2022). European MPAs should be prepared to house novel species and habitats within them, while maintaining the levels of protection and monitoring afforded to current conservation features.

Human activities such as overfishing, coastal development, and pollution create fragmented habitats, reducing the effectiveness of MPAs. To address this, MPAs must be designed to cover diverse and interconnected habitats, ensuring the protection of migratory routes, breeding grounds, and feeding areas. Comprehensive spatial planning involves integrating scientific data on marine biodiversity with socioeconomic factors to identify and prioritize areas most in need of protection.

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It also requires collaboration with local communities, stakeholders, and policymakers to balance conservation goals with sustainable use. By adopting a holistic and inclusive approach, MPAs can better withstand human pressures.

Adaptive management practices are essential for MPAs in the face of climate change (Zentner et al., 2023). This involves regular monitoring of environmental conditions and biodiversity, coupled with flexible management strategies that can be adjusted based on new scientific data. Such adaptive frameworks enable managers to respond promptly to unforeseen changes, such as sudden shifts in species distributions or the emergence of new stressors. Incorporating climate models and projections into planning processes helps anticipate future conditions and guides long-term conservation efforts.

5.2.8 Data collection and integration strategies

Both academic and grey literatures show that the most used type of knowledge to support MPA processes relate to the structural components of marine ecosystems, and the functional properties of the local environment. The designation and management of MPAs rely heavily on robust, specific data derived from biological, ecological, and environmental processes. Utilizing such data is crucial for identifying areas of significant biodiversity, understanding ecosystem dynamics, and assessing the impacts of human activities. Accurate and comprehensive data ensure that MPAs are strategically located to protect critical habitats, preserve species diversity, and maintain ecosystem services essential for marine life and human communities.

Biological data, encompassing species inventories, population dynamics, and genetic diversity, play a pivotal role in MPA planning (Lagabrielle et al., 2014). This information helps identify key species that are either threatened or play a critical role in ecosystem functioning (Sullivan-Stack et al., 2022). For example, areas with high concentrations of keystone species, such as corals or apex predators, are often prioritized for protection due to their disproportionate impact on the overall health and stability of the ecosystem. By understanding the biological attributes of a marine area, managers can design MPAs that effectively protect vital species and promote resilience against environmental changes and anthropogenic pressures.

Ecological data provide insights into the interactions between different species and their habitats, highlighting the complex web of life that sustains marine ecosystems (Harvey et al., 2017). Knowledge of ecological processes such as nutrient cycling, food web dynamics, and habitat connectivity is essential for creating MPAs that support the natural functioning of ecosystems (Fletcher et al., 2011). For instance, protecting nursery habitats like seagrasses, which serve as breeding grounds and nurseries for many marine species, ensures the continuity of life cycles and the maintenance of healthy fish populations. Ecological data also help in understanding the movement patterns of marine organisms, enabling the design of MPAs that facilitate ecological connectivity and support migratory routes.

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Environmental data, including information on water quality, temperature, currents, and climate patterns, are equally important for effective MPA management (Hyrenbach et al., 2000; Partelow et al., 2015; Edgar et al., 2014). These factors influence the distribution and health of marine species and habitats, and their variability can have significant implications for conservation efforts. For example, data on ocean currents and temperature gradients can inform the placement of MPAs to ensure they encompass areas that are resilient to climate change or serve as refugia for species under changing environmental conditions. Additionally, monitoring environmental parameters helps assess the effectiveness of MPAs and make necessary management strategies adjustments in response to observed changes (McCook et al., 2010).

Integrating data from biology, ecology, and environmental processes provides a holistic approach to MPA designation and management (Ruiz-Frau et al., 2015), ensuring that these protected areas are not only well-placed but also effectively managed. This comprehensive data-driven approach enables the development of adaptive management plans that can respond to new challenges and information, enhancing the long-term sustainability and effectiveness of MPAs (Hidalgo et al., 2022). By basing MPA decisions on solid scientific data, policymakers and practitioners can create resilient marine environments that support biodiversity, sustain fisheries, and provide critical ecosystem services for future generations.

5.3 Temporal adaptability of marine protected areas

Temporal adaptability refers to the ability of MPAs to adjust their protection measures and boundaries in response to temporal changes such as seasonal variations, climate change impacts, and migratory patterns of marine species. Temporal adaptability ensures that MPAs can remain effective in conserving marine biodiversity and ecosystems despite the shifting conditions and pressures they face. This section outlines key steps required to successfully improve the temporal adaptability of European MPAs. Recommendations center around supporting seasonal adjustments, climate change responses, general ecosystem monitoring, and responding to organism migratory patterns.

5.3.1 Continual data collection and site monitoring

Effective temporal adaptability of European MPAs hinges on robust and ongoing data collection efforts (Hopkins et al., 2016). These efforts are essential to capture the dynamic nature of marine ecosystems and respond to environmental changes over time. There are two primary components to this process: long-term monitoring programs and technological integration (Perera-Valderrama et al., 2020).

Establishing and maintaining sustained long-term monitoring programs is crucial for collecting consistent data over extended periods (Addison et al., 2015). Such programs are designed to track a wide range of ecological and environmental parameters, including species populations, habitat conditions, water quality, and climate variables. Long-term data collection allows managers to establish baselines and identify trends, which are essential for understanding the natural variability

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of ecosystems and the impacts of human activities (Perera-Valderrama et al., 2020). For example, consistent monitoring can reveal shifts in species distributions, changes in breeding patterns, or the emergence of new threats such as invasive species. By maintaining continuous records, long-term monitoring provides a comprehensive picture of the health and status of marine environments, enabling more informed and proactive management decisions.

Reliable, accurate, and consistent data collection is fundamental for using functional indicators effectively (Dunham et al., 2020). This involves employing robust monitoring methods such as scientific surveys, remote sensing, and automated data collection systems. Ensuring high-quality data requires standardized protocols, allowing data transferability and compatibility between sampling periods and locations. Additionally, long-term data sets are key for detecting trends and making informed management decisions (Hayes et al., 2019). Collaborations with research institutions and citizen science initiatives can also enhance data collection efforts. Historical data, and expert knowledge are also highly valuable to complement and supplement MPA process needs.

Technology plays a pivotal role in enhancing the temporal adaptability of MPAs. Modern technologies such as remote sensing and satellite imaging offer sophisticated tools for gathering real-time data on a wide range of oceanographic variables and species distributions (Kachelriess et al., 2014; Appolloni et al., 2020). Remote sensing allows for the monitoring of large-scale environmental conditions, such as sea surface temperatures, chlorophyll concentrations, and ocean currents, which are crucial for understanding broader ecological changes. Satellite imaging offers a regional perspective, enabling the tracking of migratory species, the detection of illegal fishing activities, and the assessment of habitat changes over time (LaRue et al., 2022). By integrating these technologies into MPA management, data collection becomes more efficient, accurate, and comprehensive, supporting timely and effective responses to environmental changes.

5.3.2 Interpretation of trends and environmental information

Operationalizing ecological and environmental data to support the temporal adaptability of European MPAs involves interpreting trends in these data to inform and adjust management and design practices. This process requires a thorough understanding of historical, projected, current, and real-time data to anticipate and respond to changes in marine ecosystems effectively.

Interpreting trends requires the continuous monitoring and collection of ecological and environmental data (Lindenmayer and Likens, 2010). Ecological data might include species population sizes, distribution patterns, and fecundity, while environmental data encompasses parameters such as sea temperature, salinity, nutrient levels, and currents. This data collection is crucial for identifying baseline conditions and detecting deviations that might signal ecological shifts or environmental changes.

Once data is collected trend analysis can occur. By applying statistical methods and modeling techniques, managers can identify patterns and trends over time. For example, a consistent rise in sea temperatures might be detected through long-term data analysis. Or an increase in abundance

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of an invasive organism. Such a trend could indicate potential impacts on marine ecosystems, necessitating a review of current MPA boundaries, management measures, or the implementation of seasonal protection measures. Similarly, trends in species population data, such as declining numbers of a key predator, might suggest ecosystem imbalances or overfishing, prompting targeted conservation actions. Managers and other MPA practitioners do not need to specifically apply statistical methods or modelling and can resort to simple comparisons between two time points based on their own expert understanding of the marine ecosystem in question.

Ecological and environmental data trend implementation must then be integrated into the operational management of MPAs (Fox et al., 2014). This involves setting management and reviewing goals that are responsive to identified trends. For instance, if data reveals a seasonal increase in phytoplankton blooms associated with nutrient runoff, MPA managers might enforce stricter pollution controls during those periods or attempt to speak with terrestrial authorities. Similarly, if the data indicates the arrival of migratory species at specific times of the year, temporary protection zones or permitting approaches can be established to safeguard critical habitats during these periods (Reynolds et al., 2017).

Effective communication and collaboration are essential for operationalizing ecological and environmental data. MPA managers must work closely with scientists, local communities, and stakeholders to interpret data and trends accurately and to ensure that management strategies are feasible and supported (Gerhardinger et al., 2009). This collaborative approach ensures data-driven decisions are well-informed and accepted, enhancing the effectiveness of temporal adaptability measures and promoting their uptake.

5.3.3 Climate change and human related pressures

The temporal adaptability of European MPAs is crucial in responding to emerging and sometimes unpredictable impacts of climate change and other human pressures. Many MPAs are established without recognition of the potential impacts of climate change on their conservation features (Schmidt et al., 2022). And the status quo of MPAs globally has been to establish them to restore an ecosystem to a historical point or maintain a current ecological baseline, with limited consideration of future impacts like climate change. But current management plans and strategies can be modified to support MPA resilience to climate change. The IPCC has concluded that European seas, particularly the Mediterranean are vulnerable to climate change impacts (Pörtner et al., 2022). Continental Europe is warming faster than the projected global average, and we have already seen extreme heatwave conditions such as summer 2023 in the Mediterranean. Utilizing climate change-related data, such as sea surface temperature, ocean acidification levels, and shifting species distributions, can significantly enhance the ability of MPAs to adapt over time (Hoppit et al., 2022). This approach allows for the implementation of flexible management strategies that can be adjusted as environmental conditions evolve, thereby ensuring the continued protection of marine biodiversity and ecosystems.

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In considering the temporal adaptability of MPAs under various human pressures, "what if" scenarios offer valuable insights. What if coastal development continues at its current pace? MPAs might struggle to maintain biodiversity as habitat loss accelerates. Conversely, what if stringent pollution controls are implemented? MPAs could see a rapid recovery of marine life, enhancing resilience against climate change. Another scenario: what if sustainable fishing practices are widely adopted? This could lead to healthier fish populations within and outside MPAs, supporting both conservation goals and local economies. Exploring these scenarios underscores the need for adaptable, forward-thinking management strategies that can respond to shifting human activities and environmental conditions, ensuring the long-term effectiveness of MPAs.

One way to support the temporal adaptability of MPAs is through the integration of real-time environmental monitoring systems. Remote sensing approaches can continuously collect data on various climate indicators. This information can be used to detect and predict changes in ocean conditions, such as temperature anomalies, shifts in current patterns, and the frequency of extreme weather events. By analyzing these data, managers can anticipate potential threats to marine habitats and species, enabling proactive measures (if possible) to mitigate adverse effects.

Climate models and forecasting tools play a vital role in supporting the temporal adaptability of MPAs (Green et al., 2014). These models can simulate likely future climate scenarios based on different greenhouse gas emission trajectories, providing insights into how marine environments might change in the coming decades. By incorporating climate projections into MPA management plans, decision-makers can design adaptive strategies that are resilient to future uncertainties (Ban et al., 2016). For example, establishing dynamic boundaries for MPAs that can be adjusted based on predicted changes in species distributions and habitat conditions ensures that protection efforts remain effective even as the environment changes. Data can also be used to identify synergistic and antagonistic climate related interactions with anthropogenic stressors, to locate hotspots where marine ecosystems are particularly vulnerable.

5.3.4 Integration of data to support adaptation

From an ecological perspective, data on species distributions and population dynamics are crucial for understanding how marine organisms use different habitats over time (Robinson et al., 2011). Technologies such as satellite tracking, acoustic telemetry, and genetic studies provide detailed insights into the migratory patterns, breeding sites, and foraging areas of marine species. For instance, tracking the movements of sea turtles or migratory fish and bird species can reveal critical temporal patterns that necessitate seasonal adjustments in MPA boundaries or regulations. This ensures that protection measures are in place during key periods, such as breeding or spawning seasons, when species are most vulnerable.

Environmental data, including parameters like sea surface temperature, salinity, dissolved oxygen levels, pH, and ocean currents, tidal gauges (sea-level rise), are equally important (Melo-Merino et al., 2020). These variables influence the distribution and behavior of marine species and the overall

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health of marine ecosystems. Advanced remote sensing technologies and in-situ monitoring systems, and buoys, provide real-time data on these environmental conditions. By analyzing this data, MPA managers can identify trends and predict changes that might affect marine life (Cvitanovic et al., 2014). For example, rising sea temperatures due to climate change can lead to shifts in species distributions, prompting a need for temporal adjustments in MPA management to accommodate these changes.

Integrating ecological and environmental data allows for a holistic understanding of marine ecosystems, facilitating adaptive management strategies (Schultz et al., 2015). Predictive modeling and data analytics play a crucial role in this process, enabling the simulation of various scenarios and their potential impacts on marine ecosystems. These models can predict how environmental changes, such as ocean acidification or warming temperatures, might affect the distribution and health of marine species. Consequently, MPA managers can proactively adjust management measures, such as modifying protection zones or implementing seasonal restrictions, to mitigate these impacts (Gerhardinger et al., 2009).

Integrating these datasets supports a more nuanced approach to conservation, recognizing the interconnectedness of marine ecosystems. For example, changes in predator-prey dynamics due to shifting species distributions can have cascading effects on the entire ecosystem. By understanding these relationships through integrated data, managers can anticipate and respond to such changes, ensuring the resilience and health of marine ecosystems within MPAs.

Predictive modeling is a powerful tool for operationalizing functioning indicators. By integrating functioning indicator data into predictive models, MPA managers can simulate future scenarios and assess potential outcomes of different management strategies (Fulton et al., 2015). These models can help predict the impacts of climate change, overfishing, or pollution on key ecosystem functions, providing a proactive approach to management. Predictive modeling also allows managers to test the effectiveness of proposed interventions before implementing them in the field. Other approaches could be mapping of key stresses guided by expert knowledge.

5.4 Using functional, functioning, and ecosystem-based indicators

Using functional, functioning, and ecosystem-based indicators is crucial for effectively managing European MPAs. Functional indicators should reflect key species roles, such as herbivores controlling algal growth, helping guide MPA design to protect areas critical for maintaining these functions. Functioning indicators measure ecosystem processes like nutrient cycling and primary production, providing insights into health and stability and informing adaptive management strategies. Ecosystem-based indicators consider species interactions and their cumulative contributions. By incorporating these indicators, European MPAs can maintain ecological integrity and resilience, preserving the vital roles species and ecological processes play in ecosystem functioning.

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5.4.1 Functional indicators

Selecting the appropriate species for monitoring is crucial. Functional indicators should focus on species that play significant roles in ecosystem processes, such as keystone species (Hermosillo-Núñez et al., 2018). These species often have disproportionate effects on ecosystem structure and function. For instance, herbivorous fish that control algal growth or apex predators that regulate prey populations are essential for maintaining ecosystem balance. Identifying and monitoring these species can provide valuable insights into the overall health of the ecosystem (Ortiz et al., 2023).

Functional diversity refers to the range of different functional roles within an ecosystem. High functional diversity typically indicates a resilient ecosystem capable of withstanding disturbances (Goswami et al., 2017). When assessing functional indicators, it is important to measure not just the presence of key species but also the diversity of functional roles they represent. This involves understanding the various ecological niches and the interdependencies among species. MPAs should aim to preserve or enhance functional diversity to maintain ecosystem resilience and adaptability.

Understanding how disturbances affect functional roles is essential for all MPA processes (Visalli et al., 2020). Disturbances such as overfishing, habitat destruction, and climate change can alter the abundance and distribution of functionally important species (Cáceres et al., 2020; Galván et al., 2022). In keeping with previous examples, overfishing of herbivorous fish can lead to algal overgrowth, which can smother habitats and cause ecosystem shifts. Monitoring changes in functional indicators can help MPA practitioners identify early signs of ecosystem degradation and implement timely management interventions to mitigate negative impacts. This is particularly important for MPA reviewing processes, to better understand the impacts that management measures may be having on marine ecosystems and conservation features.

Functional indicators should be aligned with the specific management goals of the MPA (Grorud-Colvert et al., 2021). For instance, if the goal is to maintain biodiversity, indicators might focus on species that contribute to ecosystem complexity and resilience. If the objective is sustainable fisheries, indicators might track species that are critical for fishery productivity and ecosystem health. Clear management goals help prioritize which functional indicators to monitor and how to interpret the data in the context of conservation and resource management (Dunham et al., 2020). European MPAs are often established for conservation features outlined in the Birds and Habitats Directives. Therefore, the current MPA strategy for functional indicators centers around monitoring these features in terms of population dynamics, and general health. The wider scientific view is that MPAs need to shift towards more holistic understandings of the marine ecosystem itself, not just specific conservation features.

5.4.2 Functioning indicators

Using functioning indicators to operationalize the use of ecological and environmental data in European MPA processes involves several key considerations. These indicators focus on the

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processes and functions occurring within ecosystems, such as primary production, nutrient cycling, and decomposition, providing a deeper understanding of ecosystem health and resilience.

A key consideration is examining process measurements, using functioning indicators for identifying and accurately measuring key ecological processes relevant to the MPA (Visalli et al., 2020; Grorud-Colvert et al., 2021). This involves selecting indicators that reflect essential ecosystem functions, such as primary production, which can be measured through chlorophyll-a concentrations as a proxy for phytoplankton biomass, or rates of nutrient cycling, which can be assessed through measurements of nitrogen and phosphorus levels. It’s crucial to use reliable and validated methods for data collection to ensure accurate and consistent results (Earp and Liconti, 2020). This often involves a combination of in-situ measurements, remote sensing technologies, and laboratory analyses.

Understanding natural temporal variability in ecosystem functions is essential for interpreting functioning indicators correctly (Smit et al., 2021). Marine ecosystems are dynamic, with processes that can vary on a range of timescales, seasonally, annually, or even in decades. MPA practitioners need to distinguish between natural fluctuations and significant anthropogenically driven changes that might indicate ecosystem stress or degradation (Simeoni et al., 2023). Long-term monitoring programs are invaluable in this regard, as they provide a baseline against which current data can be compared. This helps in identifying abnormal patterns or trends that require management intervention.

Functioning indicators must account for the impacts of human activities on marine ecosystem processes in and around MPAs (Dunham et al., 2020). Activities such as fishing, coastal development, pollution, and climate change can significantly alter ecosystem functions (Smit et al., 2021). For example, nutrient runoff from agriculture or discharged from rivers can lead to eutrophication and harmful algal blooms, disrupting normal nutrient cycling. By monitoring these impacts, MPA managers can identify areas where human activities are negatively affecting ecosystem functions and take appropriate management actions, such as implementing pollution controls or adjusting fishing regulations to mitigate these effects.

Continuous, long-term monitoring is critical for the effective use of functioning indicators (Grorud-Colvert et al., 2021). This allows for the detection of trends and changes over time, providing a comprehensive understanding of how ecosystem functions evolve. Long-term datasets are particularly valuable for assessing the cumulative impacts of environmental stressors and management actions. Establishing robust monitoring programs with consistent methodologies ensures that data is comparable over time, facilitating more accurate assessments and informed decision-making.

5.4.3 Ecosystem-based indicators

Ecosystem-based indicators differ from more basic quantitative biological and physical indicators by having a broader ecosystem scale context, better ability to capture the overall health and

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functionality of an ecosystem and can consider interactions like those between species and habitat dynamics (McDonald et al., 2020). Using ecosystem-based indicators to operationalize the use of ecological and environmental data in European MPAs is a crucial strategy for effective management and conservation. These indicators serve as practical tools that synthesize complex ecological data into comprehensible metrics, enabling managers to make informed decisions. By providing a holistic view of ecosystem health, these indicators help assess the effectiveness of conservation measures, guide adaptive management, and ensure the sustainability of marine resources (Belgrano et al., 2021).

One of the primary benefits of ecosystem-based indicators is their ability to integrate multiple facets of ecological and environmental data (Culhane et al., 2020). This includes biological variables such as species abundance and diversity, physical parameters like water temperature and salinity, and chemical factors such as nutrient levels and pollutants. By aggregating this diverse data, indicators can reveal patterns and trends that might be missed when considering individual parameters in isolation. For example, a decline in a particular fish population might be better understood in the context of changes in water quality and habitat conditions, allowing managers to address the root causes of the problem more effectively.

Moreover, ecosystem-based indicators facilitate the monitoring and evaluation of MPAs by providing benchmarks against which changes can be measured (Williams et al., 2021). These indicators can track progress towards conservation goals, such as the recovery of endangered species or the restoration of degraded habitats. They also enable the detection of early warning signs of ecological stress or degradation, allowing for timely interventions. For instance, a sudden shift in the composition of benthic communities could indicate deteriorating water quality or increased sedimentation, prompting further investigation and remedial action.

The use of ecosystem-based indicators also supports stakeholder engagement and communication. By translating complex scientific data into understandable metrics, these indicators can enhance the transparency and accountability of MPA management. Stakeholders, including local communities, policymakers, and conservation organizations, can more easily grasp the status and trends of marine ecosystems, fostering a shared understanding and support for conservation efforts. For instance, visual tools such as dashboards and scorecards that display indicator trends can effectively communicate the health of MPAs to a broad audience.

5.5 The use of local and traditional knowledge to inform the design and management of marine protected areas

A clear bias from our examination of academic and grey literatures is that scientific knowledge and expert knowledge is recommended and the most used in European MPAs in practice. However, scientific and expert knowledge are components of a top-down approach to MPA designation and management. Other fields like research into adaptive governance and management, which are recognized as practices desirable to adopt for protected areas to enhance their resilience to

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disturbances and promote adaptation to climate change, advocate for a combination of top-down and bottom-up approaches. Key to bottom-up approaches are the engagement of local communities and using local knowledge of the area to better design and manage MPAs. This approach will also help better address the needs of stakeholders.

5.5.1 Combining scientific with local knowledge

Combining scientific knowledge with local expert knowledge is essential to operationalize the use of ecological and environmental data in European MPA processes (Boubekri et al., 2022; Katsanevakis et al., 2020). This integration enhances the understanding of marine ecosystems, enriches data quality, and promotes more inclusive and sustainable management practices. Scientific knowledge provides a robust foundation based on systematic observations, experimental data, and advanced analytical techniques. It offers detailed insights into ecological dynamics, species distributions, and environmental conditions, which are critical for designing and managing MPAs. However, scientific data often have spatial and temporal limitations, especially in remote or less-studied marine regions (Ramírez et al., 2022).

Local expert knowledge, accumulated through generations of interaction with marine environments, fills these gaps by offering nuanced, context-specific information that might not be captured through scientific methods alone (Cebrián-Piqueras et al., 2020). Local expert knowledge includes valuable insights on historical ecosystem changes, species behaviors, and local environmental patterns. For example, local fishers can provide detailed accounts of fish spawning seasons, migration routes, and traditional fishing grounds that are crucial for defining MPA boundaries and regulations. By incorporating local expert knowledge, MPA planners can create management strategies that are better aligned with ecological realities and local socio-cultural contexts, ensuring greater compliance and support from local communities (Djosetro and Behagel, 2024).

Effective integration of scientific and local knowledge requires a collaborative approach that respects and values both types of knowledge (Hill et al., 2020). This involves establishing co-management frameworks where scientists, local experts, and stakeholders jointly participate in data collection, analysis, and decision-making processes. Co-management fosters mutual learning and trust, ensuring that MPA strategies are both scientifically sound and locally relevant (Masud et al., 2022). For instance, community workshops and participatory mapping exercises can be used to gather local expert knowledge and validate it against scientific data, leading to more comprehensive and accurate ecological assessments.

The integration of citizen science data into formal datasets requires careful validation to ensure accuracy and reliability (Fraisl et al., 2022). Training programs can be implemented to educate citizen scientists on data collection protocols and quality control measures. Additionally, technological tools such as mobile apps and online platforms can facilitate standardized data submission and real-time feedback. By validating and incorporating citizen science data, MPAs can

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address issues of patchy data coverage and make more informed management decisions (Gotama et al., 2023). This approach enriches the scientific knowledge base and enhances the adaptive management of marine resources, contributing to the resilience and sustainability of marine ecosystems.

5.5.2 Stakeholder engagement

Stakeholder engagement is crucial for operationalizing the use of ecological and environmental data to support the integration of local expert knowledge in European MPA processes (Pelletier 2020). Effective stakeholder engagement ensures that the perspectives, knowledge, and needs of all relevant parties, particularly local communities, are considered in MPA planning and management (Di Franco et al., 2020). This inclusive approach fosters a sense of ownership and responsibility among stakeholders, leading to more sustainable and resilient MPA outcomes.

Engaging stakeholders from the outset allows for the collection and validation of comprehensive and diverse data sets (Custodio et al., 2022). Local communities, fishers, indigenous groups, and other stakeholders possess invaluable local expert knowledge that complements scientific data. This knowledge includes detailed observations on species behavior, habitat conditions, and historical environmental changes, which are essential for accurate ecological assessments and effective MPA design. By actively involving stakeholders in data collection and analysis, MPA managers can ensure that management plans are grounded in both scientific evidence and local realities, leading to more accurate and context-specific conservation strategies (Maestro et al., 2022).

Stakeholder engagement enhances the legitimacy and acceptance of MPAs. When stakeholders are involved in the decision-making process, they are more likely to support and adhere to MPA regulations and management practices (Katikiro et al., 2021). This is particularly important for local communities whose livelihoods and cultural practices are directly impacted by MPAs. Inclusive participation helps build trust and reduces conflicts, as stakeholders feel their voices are heard and their concerns addressed (Bennett et al., 2021). For example, involving local fishers in the delineation of MPA boundaries and the establishment of no-take zones can help balance conservation goals with socio-economic needs, ensuring that MPAs contribute to both biodiversity conservation and sustainable development.

Stakeholder engagement facilitates adaptive management, which is vital for the dynamic and complex nature of marine ecosystems (Eaton et al., 2021). Continuous dialogue and collaboration with stakeholders enable MPA managers to gather real-time feedback and local observations, which can be integrated with scientific monitoring to adjust management practices as needed. This adaptive approach ensures that MPAs remain effective in the face of environmental changes and emerging challenges. For instance, local fishers can report shifts in fish populations or new threats, such as illegal fishing activities, allowing for timely interventions and adaptive management responses.

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5.5.4 Capacity building

Capacity building is crucial for helping use local expert knowledge to operationalize the use of ecological and environmental data in MPA processes. By enhancing the skills, knowledge, and resources of local communities and stakeholders, capacity building ensures that local expert knowledge is effectively utilized alongside scientific data, leading to more comprehensive and sustainable MPA management.

One of the primary aspects of capacity building is education and training. Providing local communities with training on scientific methods, data collection techniques, and conservation practices empowers them to actively participate in MPA processes (O'Connor et al., 2024). This training can include workshops on species identification, habitat monitoring, and the use of technology such as GPS and data logging devices. By equipping local stakeholders with these skills, they can contribute valuable data that complements scientific research, leading to a more holistic understanding of marine ecosystems. For instance, trained local fishers can systematically record observations on fish populations and environmental conditions, providing real-time data that enhances ecological assessments and management decisions.

Capacity building also involves fostering mutual learning between scientists and local communities (Dalton et al., 2020). Scientists can learn from the extensive experiential knowledge of local experts, gaining insights into long-term ecological changes and culturally significant practices. This reciprocal exchange of knowledge promotes mutual respect and collaboration, ensuring that local expert knowledge is integrated into MPA processes in a meaningful and respectful manner. Collaborative research projects, where scientists and local experts work together to address specific conservation challenges, can be particularly effective in building this mutual understanding and respect.

Providing resources and support is another critical component of capacity building. Local communities often need access to financial resources, equipment, and technical support to effectively participate in MPA management (Di Franco et al., 2020). Ensuring that these resources are available helps sustain community engagement and the integration of local expert knowledge. For example, funding can be allocated to support local monitoring programs, purchase necessary equipment, and facilitate ongoing training initiatives. Additionally, establishing support networks that provide technical assistance and guidance can help local communities navigate complex management processes and contribute effectively to MPA governance (Collier et al., 2020).

Building institutional capacity within local governance structures is also essential. Strengthening local institutions, such as community-based organizations and fisheries cooperatives, enables them to play a more active and influential role in MPA management (Bennett et al., 2021). This can be achieved through organizational development programs that enhance leadership, management, and advocacy skills. Strong local institutions can effectively represent community interests, advocate for the incorporation of local expert knowledge, and ensure that management decisions are aligned with local priorities and sustainable practices.

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6. Operational Recommendations

6.1 Recommendation 1: From "feature protection" to "ecosystem process protection"

A central finding of this deliverable is that European MPAs predominantly rely on structural ecological indicators, species presence, abundance, and habitat extent, when designing, monitoring, and reviewing protected areas. While these indicators are important and relatively easy to collect, they do not adequately capture how ecosystems function, nor how resilient they are to pressures such as climate change, fishing, or pollution. Scientific literature increasingly emphasizes that the protection of ecosystem processes, like productivity, nutrient cycling, carbon storage, trophic regulation, and habitat-forming interactions, is more informative for long-term conservation success than focusing solely on individual species or habitats. The gap is therefore not a lack of monitoring, but that existing monitoring outputs are interpreted through a structural rather than a functional lens.

In practice, this shift does not require new surveys or expensive methodologies. Most MPAs already monitor key species and habitats. The operational change lies in reinterpreting these observations by grouping monitored species into functional roles (e.g. primary producers, grazers, bioturbators, predators, habitat-formers) and linking habitat monitoring to the ecosystem processes those habitats support. For example, seagrass monitoring can be reframed as an indicator of carbon sequestration capacity; reef fish surveys can be interpreted in terms of trophic structure and grazing pressure; benthic invertebrate surveys can indicate sediment mixing and nutrient cycling. This reclassification can be achieved using existing trait databases and published ecological knowledge without additional field effort.

Management reporting should therefore move beyond statements such as "species abundance stable" or "habitat extent unchanged," and instead report on the status of functional groups and the ecosystem processes they underpin. By doing so, managers gain a clearer understanding of whether the MPA is maintaining ecosystem functioning, not merely protecting ecological features. This provides a more robust basis for adaptive management decisions, particularly under changing environmental conditions where species compositions may shift but ecosystem processes must be maintained for conservation objectives to be achieved.

6.2 Recommendation 2: Integrating ecological connectivity into everyday marine protected areas practice

The gap analysis shows that ecological connectivity is widely recognized in the scientific literature as fundamental to effective MPAs, yet is rarely operationalized in European MPA processes because it is perceived as technically complex, data-intensive, and dependent on specialist modelling or genetic studies. In practice, this perception creates a barrier that prevents managers from engaging with connectivity at all. The key finding of this deliverable is that meaningful integration of

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connectivity does not need to begin with advanced methods. Instead, it can start by reinterpreting information that MPAs already possess, habitat maps, species monitoring data, and published life-history knowledge, to understand how ecological movements relate to MPA boundaries.

A practical first step is to use existing habitat distribution maps to identify structural connectivity: continuous habitats, migration corridors, nursery areas, and feeding grounds that extend beyond or link protected sites. This alone can reveal whether the MPA is ecologically isolated or embedded within a broader connected seascape. The second step is to incorporate functional connectivity proxies drawn from published ecological knowledge. For key species of conservation or management interest, information on dispersal distances, spawning migrations, seasonal movements, or larval duration is readily available in scientific literature and does not require new data collection. Overlaying this knowledge with MPA boundaries often immediately highlights where important ecological processes occur outside the protected area.

This information can then directly inform management decisions without requiring complex analysis. Managers can use connectivity insights to guide zoning, identify the need for buffer areas, prioritize cooperation with neighboring MPAs or fisheries authorities, and interpret monitoring results in a broader spatial context. For example, if adults of a protected fish species are monitored inside the MPA but known nursery grounds lie outside, this indicates a clear connectivity gap that can be addressed through spatial planning or seasonal protection measures. In this way, connectivity becomes a routine consideration in management discussions rather than an abstract ecological concept reserved for scientific studies.

6.3 Recommendation 3: Make monitoring coherent, comparable, and decision-relevant

The review of grey literature shows that most European MPAs undertake some form of ecological monitoring, yet these activities are often fragmented, inconsistently applied over time, and poorly linked to management decisions. Indicators are frequently listed in monitoring plans without a clear explanation of what management question they are intended to answer, how often they should be measured, or how the results should influence management action. The problem is therefore not the absence of monitoring, but the absence of structure that makes monitoring outputs operationally meaningful for managers.

A practical improvement begins by explicitly defining the purpose of each monitored indicator. For every survey or dataset, managers should be able to state: *what management decision does this inform?* This simple step aligns monitoring with decision-making rather than data collection for its own sake. Establishing minimum temporal standards (e.g. annual benthic surveys, seasonal species surveys, regular water quality measurements) further ensures that data are comparable through time and can reveal ecological trends rather than isolated observations. Where possible, monitoring should also occur both inside and outside the MPA, allowing managers to distinguish broader environmental change from the specific effect of protection.

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Finally, monitoring data must be stored and reported in ways that support review cycles and adaptive management. Linking datasets to accessible repositories such as national databases or European data infrastructures ensures continuity and transparency. More importantly, monitoring results should become a formal input into periodic management plan revisions, so that evidence of ecological change directly triggers discussion of management responses. When monitoring is structured in this way, it becomes a decision-support tool rather than a reporting obligation, allowing MPAs to respond more effectively to ecological change and human pressures.

6.4 Recommendation 4: Explicitly incorporate abiotic drivers and human pressures

The gap analysis demonstrates that, while biotic features dominate MPA monitoring and reporting, abiotic drivers and human pressures are comparatively under-represented in both planning and management processes. This is problematic because ecosystem change within MPAs is often driven as much by physical conditions and external pressures as by biological dynamics. Temperature trends, hydrodynamics, sediment stability, fishing intensity, pollution inputs, and coastal development frequently determine whether ecological objectives can be achieved, yet these factors are rarely integrated into routine MPA decision-making. The result is that managers monitor ecological symptoms without systematically assessing the underlying drivers.

A practical first step is to incorporate a small set of core abiotic indicators into existing monitoring frameworks. Parameters such as sea temperature trends, current regimes or exposure, and substrate or sediment condition can often be sourced from existing national oceanographic services or European platforms such as Copernicus and EMODnet, without the need for new field surveys. Including these variables alongside ecological indicators provides essential context for interpreting ecological change and understanding whether observed trends are driven by local management issues or broader environmental shifts.

In parallel, MPAs should spatially map the distribution of key human pressures affecting their sites, such as fishing activity, pollution sources, coastal infrastructure, and noise or energy inputs. Overlaying these pressure maps with ecological and functional indicators allows managers to identify where pressures intersect with ecologically important areas. This supports more targeted management responses, such as enforcement prioritization, zoning adjustments, or engagement with external authorities. By routinely considering abiotic conditions and human pressures alongside biological monitoring, MPAs can move from reacting to ecological change to proactively managing the drivers that shape it.

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