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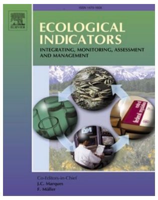

Original Articles

Enhancing marine protected areas with effective ecological and environmental data integration

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ABSTRACT

Marine Protected Areas (MPAs) play a critical role in marine conservation, but their effectiveness, among other things, depends on robust ecological and environmental data integration. This paper explores key gaps and suggests ways forward for evaluating MPA ecological functionality, emphasizing the integration of species and habitat functional roles, process-based, and ecosystem-based indicators to assess species roles and ecosystem processes when identifying areas for conservation and supporting their management and governance. Connectivity is highlighted as a fundamental process, ensuring MPAs contribute to broader ecological coherence rather than acting as isolated spatial units. Given the dynamic nature of marine ecosystems, temporal adaptability, supported by long-term monitoring and data-driven decision-making, is essential for maintaining resilience amid climate change and anthropogenic pressures. Additionally, leveraging local and traditional knowledge through stakeholder engagement enhances MPA governance and implementation. By combining a diverse range of ecological indicators to aid decision-making, we can improve MPA effectiveness, ensuring they sustain biodiversity, ecosystem services, and resilience in the face of environmental change.

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1. Introduction

Marine Protected Areas (MPAs) are essential tools for conserving marine biodiversity, managing fishery resources, and safeguarding the healthy functioning of marine ecosystems and their services (Cannizzo et al., 2025; Fan et al., 2023; Simeoni et al., 2023). Over the past few decades, progress has been made in establishing MPA networks globally, supported by increasing awareness of their role in protecting vulnerable marine habitats and species. However, the effectiveness of these areas in achieving their ecological and conservation objectives remains variable, and often limited, due in part to enduring gaps in the practical integration of ecological and environmental knowledge into MPA processes (here defined as wider governance approaches which involve MPA planning, designation, assessment, monitoring, implementation, and evaluation/ reviewing) (Grorud-Colvert et al., 2021; Ferreira et al., 2022; Edgar et al., 2014).

Current MPA processes tend to focus heavily on static, structural, and taxonomic attributes, such as species richness, presence of iconic or endangered species, and broad habitat classifications, as primary criteria for site selection and monitoring (Smit et al., 2021; Bianchi et al., 2022). These indicators aid in establishing baseline biodiversity and habitat conditions, but they often fall short of capturing the dynamic and interconnected nature of marine ecosystems. As a result, many MPAs are designed and assessed without sufficient consideration of the functional roles species play, the ecological processes that underpin resilience, or the spatial and temporal patterns of connectivity that sustain ecosystem health (Puig-Gironès and Real, 2022; Nicholson et al., 2021; Balbar and Metaxas 2019). This would help to support ecologically coherent and effective networks, as called for under international frameworks such as the Kunming-Montreal Global Biodiversity Framework, particularly Target 3, which aims to conserve at least 30 % of marine and coastal areas by 2030 through effective, well-connected, and equitably managed systems of protected areas.

This overreliance on structural metrics has contributed to a persistent gap in the operationalization of ecosystem-based management principles within MPAs (Cormier et al., 2017). Key dimensions of ecosystem functioning, such as nutrient cycling, productivity, trophic interactions, and functional redundancy, remain underrepresented in indicator frameworks and decision-making tools. Moreover, few MPA strategies systematically incorporate measures of ecological connectivity or temporal adaptability, both of which are essential to ensuring long-term conservation success in the face of climate change and increasing anthropogenic pressures (Turnbull et al., 2021; Roberts et al., 2021; Cardoso-Andrade et al., 2022). Addressing these limitations is essential for transitioning MPAs from static conservation zones to adaptive, process-oriented management tools. As human activities and climate change continue to intensify pressures on marine systems, MPAs must evolve beyond static, structure-oriented approaches. There is a growing recognition that assessing MPA effectiveness requires more than just tracking species numbers or habitat extent, it demands a deeper understanding of how ecosystems function, species interactions, and system responses to stress and disturbance. Functional and process-based indicators, such as trophic relationships, ecological traits, or primary productivity, provide the kind of mechanistic insights necessary to evaluate resilience and support adaptive management strategies (Flensborg et al., 2023; Smit et al., 2021).

In parallel, the fragmented nature of governance systems and limited transferability of scientific data into policy-relevant formats hinders the systematic application of ecological insights in MPA governance. Even when robust data are available, mismatches between data resolution, management needs, and institutional capacity often mean they remain underused or disconnected from real-world decision-making (Grorud-Colvert et al., 2021; Kachelriess et al., 2014; Appolloni et al., 2020).

In response to these challenges, this perspective paper offers a synthesis of emerging approaches that can strengthen the ecological and environmental foundations of MPA planning and evaluation. Our aim is to advance the integration of state-of-the-art ecological knowledge and data into MPA decision-making, adopting a process-based perspective that moves beyond temporally static, spatially restrictive approaches solely informed by structural indicators toward a more dynamic, systems-based understanding of ecosystem health. We address and propose strategies for advancing four key dimensions: (1) integrating functional indicators to better capture species ecological roles and interactions; (2) operationalizing ecological connectivity to design spatially coherent MPA networks; (3) enhancing temporal adaptability to accommodate shifting baselines and ecosystem dynamics; and (4) incorporating local and traditional knowledge to support context-sensitive and inclusive governance. Together, these elements provide pathways toward more resilient, adaptive, and effective MPAs that deliver long-term conservation outcomes in a changing ocean.

2. Towards the effective consideration of ecological functioning in marine protected areas

Increasing attention is being paid to the integration of functional, process-oriented, and ecosystem service-based indicators in the design and evaluation of MPAs (Bianchi et al., 2022; Flensborg et al., 2023; Turnbull et al., 2021). However, MPA frameworks have historically focused on taxonomic diversity, emphasizing species presence, abundance, and richness, while often overlooking the ecological roles and interactions that underpin ecosystem functioning. Functional approaches, which incorporate biological traits such as mobility, reproductive strategy, or trophic role, offer a more nuanced understanding of how species contribute to key ecosystem processes (Mitta et al., 2021). Considering functional diversity in MPA planning can improve the representation and protection of critical ecosystem functions, support resilience to environmental change, and enable more adaptive and robust conservation strategies. Moving from taxonomic to functional perspectives has important implications for how MPAs are sited, managed, and evaluated, especially under changing ocean conditions and shifting species distributions (Fig. 1a).

2.1. *Functional traits-related indicators*

Functional indicators assess the ecological roles species play in contributing to ecosystem processes and stability (Beauchard et al., 2017; Smit et al., 2021). Unlike structural metrics (e.g., abundance of species), functional indicators provide information on the ecological role of species within a system, recognizing how they interact and shape their biological and physio-chemical environment (Penn et al., 2024; Miatta et al., 2021). High functional diversity often indicates a more resilient system capable of withstanding disturbances, while low functional diversity can signal ecosystem vulnerability (Vergés et al., 2014).

Key functional indicators include keystone species, ecosystem engineers, and trophic interactions. Sea stars can dominate kelp forests if there is insufficient predation (Hermosillo-Núñez et al., 2018), resulting in habitat collapse, while reef-building corals and oysters create habitats that support biodiversity (Tebbett et al., 2024; Smith and Castorani, 2023). These species exemplify functionally distinct roles that are often poorly buffered by redundancy, making ecosystems particularly vulnerable when they are lost. Auber et al. (2022) demonstrate that communities with low functional redundancy, where few species share similar ecological traits, are more prone to collapse under disturbance, as unique functions cannot be maintained once key species are lost. Incorporating trait-based assessments of functional vulnerability helps identify not just species at risk, but the potential cascading impacts on ecosystem functioning when such species are disturbed.

Trophic interactions also serve as important functional indicators, as species at different levels of the food web regulate ecosystem stability. Apex predators such as sharks and large pelagic fish control other fish populations, maintaining trophic balance (Xu and Jordán, 2024). Functional redundancy further strengthens ecosystems, as multiple

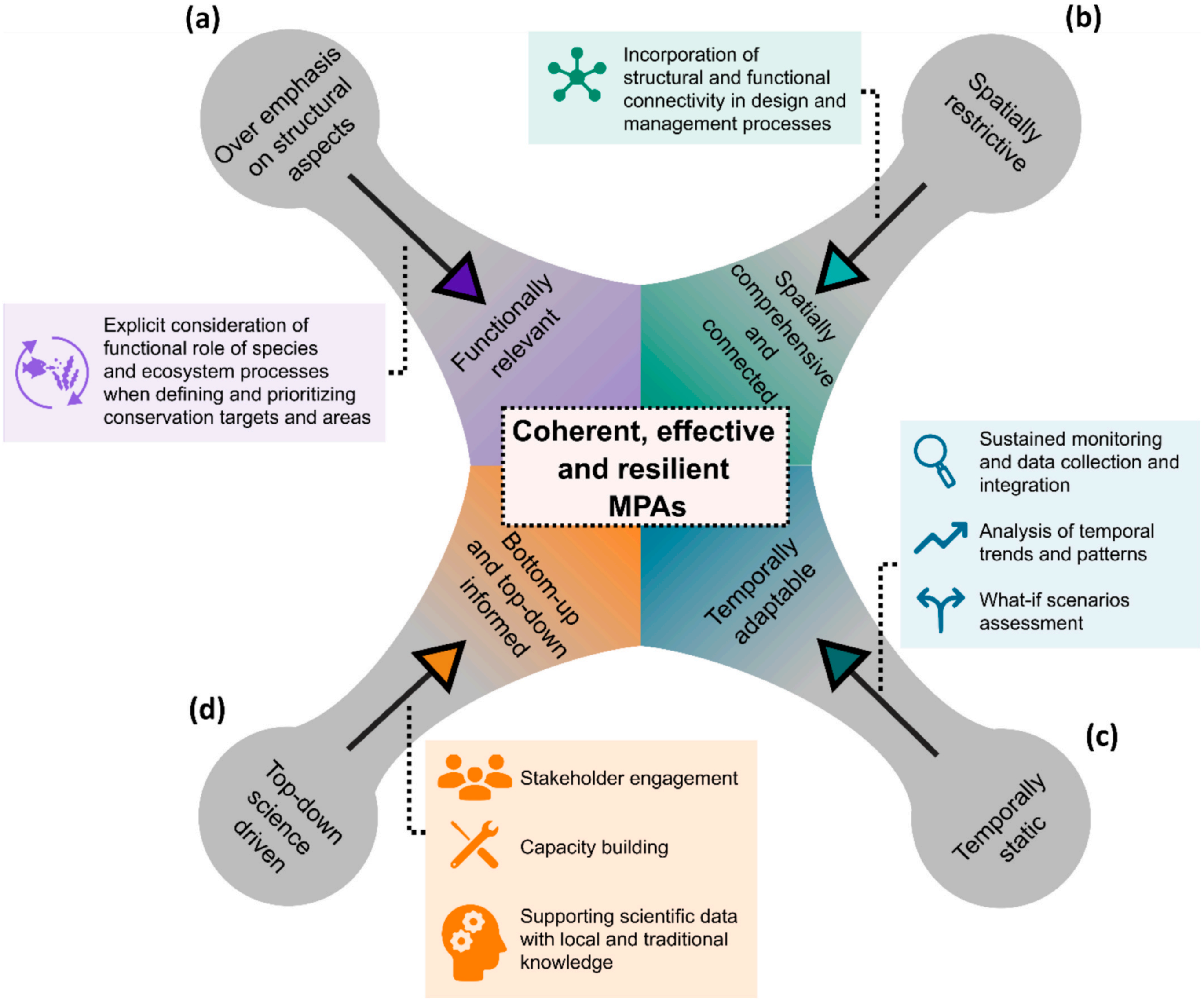

Fig. 1. A framework for integrating ecological and environmental data into adaptive MPA design. The figure is structured into quadrants, each representing a distinct pathway for ecologically improving MPA design, implementation and management. Every pathway begins with a current issue, includes a series of aspects that need to be implemented, and ends in a desired or necessary feature that MPAs should have. All pathways converge at a central point to emphasize that reaching coherent, effective, and resilient MPAs requires addressing all these pathways.

species performing similar roles can buffer against disturbances. If an herbivorous fish species declines, others can fulfil the same ecological function, preventing collapse (Whitfield and Harrison, 2021). However, understanding these dynamics requires more than species-level assessments. Broader ecological networks provide a framework to capture the structure and function of biotic interactions, identifying key nodes, interaction strengths, and redundancy within trophic pathways (Harvey et al., 2017). Network-based metrics, such as connectivity, modularity, and species centrality, can be used to assess ecosystem robustness and the potential consequences of species loss (Balbar and Metaxas 2019). Incorporating such metrics into conservation planning and MPA design offers a way to identify functionally critical species and interactions, and to prioritize areas where network integrity and ecosystem functioning are most at risk (Carr et al., 2017). This approach bridges the gap between species-focused conservation and ecosystem-level resilience, making it particularly relevant in the context of multi-species MPAs (Roberts et al., 2021).

Functional indicators are essential for evaluating MPA effectiveness. Monitoring keystone species, ecosystem engineers, and trophic dynamics can offer valuable insights into the ecosystems MPAs aim to protect. However, integrating functional traits and indicators of functional diversity, such as body size or life history strategies, provides a more robust understanding of ecosystem functioning and resilience (Bianchi et al., 2022; Miatta et al., 2021). A useful example of this approach can be seen in the Start Point to Plymouth Sound & Eddystone Special Area of Conservation (SAC) in the UK, where functional indicators are applied to assess benthic reef resilience. Long-term monitoring focuses not only on species presence but also on traits such as biomass production and recovery potential of key reef-forming organisms. These traits are directly linked to ecosystem functions, for example, high biomass production and rapid recovery rates contribute to structural stability and habitat provision. Similar approaches are outlined by Waechter et al. (2022), where trait-based analyses were used to identify functionally unique species and inform MPA network design, this application enables managers to evaluate whether fishing restrictions are enhancing functional redundancy and safeguarding critical ecological roles. By explicitly linking trait measurements to management objectives, such monitoring supports adaptive decision-making that prioritizes the protection of functions essential for long-term ecosystem resilience.

More broadly, functional indicators, such as functional traits, diversity, and redundancy, provide critical insights into how species contribute to ecosystem processes and how resilient these systems are to environmental disturbances like overfishing, habitat degradation, and climate change. By measuring changes in the range and distribution of functional traits within a community, these indicators reveal shifts in species roles and interactions that can precede visible declines in species richness or abundance (Pedersen et al., 2017; Weisberg et al., 2024). For example, a loss of functional redundancy, where multiple species perform similar ecological roles, can reduce ecosystem resilience and increase vulnerability to cascading effects following disturbance. Long-term monitoring of functional indicators thus enables MPA managers to detect early warning signs of ecosystem degradation, such as altered trophic dynamics or declining ecosystem functioning, before more obvious symptoms arise. This information supports timely adjustments to conservation measures, improving the capacity to maintain ecosystem stability and promote recovery (Smit et al., 2021).

MPA objectives can dictate which functional indicators to prioritize. Functional trait and diversity-based indicators offer a mechanistic understanding of ecosystem processes that can support targeted conservation objectives. For biodiversity conservation, metrics such as functional richness and redundancy help assess ecosystem resilience by capturing the range and overlap of ecological roles fulfilled by species (Mouillot et al., 2013). This allows managers to move beyond species counts and instead identify whether key functions such as herbivory, predation, or nutrient cycling, are at risk due to loss of unique or irreplaceable traits. For sustainable fisheries, focusing on functionally important species, such as top predators or forage fish with high interaction strength, enables the maintenance of ecosystem balance and long-term fishery productivity (Marra et al., 2016). Crucially, aligning functional indicators with specific conservation goals, whether preserving resilience, supporting ecological connectivity, or managing harvest impacts, allows for more targeted and adaptive decision-making. This ensures that marine spatial planning and MPA effectiveness are grounded in biodiversity patterns, and the processes that sustain ecosystem functioning over time.

2.2. Process-Based indicators

While functional trait-related indicators focus on species and their ecological roles, process-based indicators assess the ecological processes that sustain ecosystem functioning. These indicators track system-wide functions such as productivity, nutrient cycling, and energy transfer, providing insights into ecosystem health and stability (Wang et al., 2020). They are crucial for understanding how marine ecosystems operate and respond to environmental changes, offering a broader perspective on ecosystem resilience. To formally integrate these insights into conservation, process-based indicators can be operationalized through biogeochemical, ecological network, and dynamic energy budget models.

One key process-based indicator is primary productivity, which reflects the energy entering marine food webs. Chlorophyll-a (chl-a) concentrations, often used as a proxy for phytoplankton biomass, are widely applied to estimate productivity (Brewin et al., 2023). However, in dynamic coastal systems, chl-a can be misleading due to drift or advection, where ocean currents displace phytoplankton from production zones, leading to spatial mismatches between observed biomass and actual productivity (Tapia et al., 2009). Complementary indicators such as seagrass productivity (via biomass and carbon storage) and sediment nutrient fluxes (e.g., nitrogen fixation) can offer more localized and process-specific insights (Miyajima et al., 2022; Presley and Caffrey, 2021).

Recent advances in integrating food-web analysis with bioenergetic modelling offer powerful tools for understanding ecosystem functioning at geographic scales and linking it to conservation decision-making (Antunes et al., 2024). These approaches quantify energy fluxes between species and across trophic levels, allowing assessment of how biodiversity loss or habitat change can alter key processes such as primary production, nutrient cycling, and biomass transfer. Process-based indicators of trophic transfer and energy flow can be derived from multiple methods. For example, stable isotope analysis can track trophic linkages and estimate energy transfer efficiency (Cárcamo et al., 2024), although interpretation must account for baseline variability or omnivory, which may obscure pathways. In some cases, differences in benthic trophic levels inside and outside MPAs, as shown by Blanco et al. (2021), highlight the importance of contextual interpretation when evaluating management effectiveness. Complementary indicators, such as larval fish abundance and growth rates, can signal the productivity of plankton populations and the overall health of marine food webs (Guyah et al., 2021). Bioenergetic and food-web models can also integrate measures of ecosystem resilience, including recovery rates following disturbances; for example, coral recruitment after bleaching events can reflect a reef's capacity to regenerate after stress (Gonzalez et al., 2024). Embedding such energy-based metrics into MPA assessment frameworks can help identify sites that maintain high functional redundancy and energy transfer rates, supporting both biodiversity conservation and the ecosystem services on which people depend.A key challenge in using process-based indicators is distinguishing between natural ecosystem variability and changes driven by human activities. Marine ecosystems naturally fluctuate across seasonal to decadal timescales, making it difficult to isolate the effects of specific stressors. To address this, long-term, continuous monitoring is essential (Grorud-Colvert et al., 2021). Sustained datasets enable practitioners to establish ecological baselines, detect meaningful trends like species distribution shifts under climate change, and assess the impacts of environmental pressures and management actions (Edgar et al., 2014). This long-term perspective supports a more accurate understanding of ecosystem functional dynamics and evolution over time (Melbourne-Thomas et al., 2023).

3. Marine protected areas need to be spatially comprehensive and connected

MPAs and MPA networks, including transboundary networks, can be designed to be spatially comprehensive by incorporating ecological connectivity, ensuring movement and species interactions across different habitats and ecosystems (Balbar and Metaxas, 2019; Roberts et al., 2021; Carr et al., 2017; Gardner et al., 2024). Ecological connectivity is essential for maintaining biodiversity, enhancing the resilience of marine species to environmental changes, and supporting healthy ecosystem functions (Berkström et al., 2022; Tanner et al., 2025). To achieve this, MPAs should be designed based on a comprehensive understanding of the spatial and temporal dynamics of marine life, integrating information on life history events and their phenology (including dispersion and migration processes), critical habitat requirements, and their interactions with oceanographic processes and physico-chemical drivers (e.g., current and circulation patterns, temperature and salinity gradients) (Fig. 1b).

3.1. Overcoming marine protected area spatial restrictions via connectivity

Connectivity in marine systems can refer both to ecological processes and to the spatial arrangement of MPAs within the broader marine seascape. Ecological connectivity encompasses the movement of organisms, nutrients, and energy across habitats, which is crucial for maintaining population and community dynamics and ecosystem function (Balbar and Metaxas, 2019). However, identifying and quantifying ecological connectivity often requires substantial investment in scientific expertise and long-term monitoring (Li and Fluharty, 2017). For instance, tracking gene flow to understand population linkages necessitates time-consuming and costly sampling and molecular analysis (Sahyoun et al., 2016). Other methods are available to assess connectivity, including biotelemetry, modelling, and mark-recapture techniques (Dhellemmes et al. 2023; Thorburn et al. 2024; Hussey et al. 2015; Burgess et al., 2014; Rogers et al., 2014).

A key strategy to enhance connectivity between individual MPAs and within MPA networks is the inclusion of conservation corridors. These are pathways with suitable environmental conditions and habitats which allow species to effectively move between MPAs (Pendoley et al., 2014). Corridors are particularly crucial for species with large distributions, migratory species, and those that require different habitats at various life stages, for example, fish that use seagrass beds as nurseries and rocky reefs as adult feeding ground (D'Aloia et al., 2017). By safeguarding these pathways, MPAs can support genetic diversity and population stability, reduce local extinction risks and promote resilience against environmental stressors (Carr et al., 2017).

Alongside habitat corridors, the concept of "steppingstones" exists. Steppingstones are strategic smaller protected areas, acting as intermediate habitats for species moving between larger MPAs (Balbar and Metaxas, 2019). These areas can provide safe stopover points for rest, feeding, and breeding, especially for species undertaking long-distance migrations (Sidorenko et al., 2025). For example, fish populations can benefit from steppingstone MPAs, aiding their life cycle processes (Leiva et al., 2022).

To support connectivity effectiveness of MPAs, multi-scale connectivity must be considered (Lagabrielle et al., 2018; Gardner et al., 2024). This requires understanding ecological processes and species movements at different spatial and temporal scales. Multi-scale analysis of connectivity is essential to assess the spatial comprehensiveness of MPAs, ensuring effective protection of ecosystem services and ecological functions (Roberts et al., 2021; Christie et al., 2010).

At local scales, connectivity between individual MPAs helps link habitats, helping species move freely for feeding, shelter, and reproduction (Balbar and Metaxas, 2019). For example, many fish species depend on algal and seagrass beds for different stages of their life cycle. Maintaining connectivity between these habitats in MPAs supports local population dynamics and resilience (Carr et al., 2017), which is crucial for species relying on differing habitats for different life stages.

At larger scales, regional connectivity between MPAs aids species movement across broad geographical areas, vital for genetic diversity and population dynamics (Friesen et al., 2019). Many marine species perform long-distance migrations for their life cycles, like sea turtles. Creating ecologically connected MPA networks supports migration routes and facilitates population genetics flow (Carr et al., 2017). Regional connectivity mitigates impacts of local disturbance, like pollution or climate change effects, supporting alternative habitats and helping network wide population stability (Botsford et al., 2009).

Considering ecosystem scale connectivity requires understanding linkages between different ecosystems vital for overall marine environmental health (Sheaves 2009). For example, interactions of coastal and offshore ecosystems, like nutrient flow from estuaries to the sea, can be vital for ecosystem biodiversity and productivity. Considering such ecosystem-level connections in MPA design help protect ecological processes, moving beyond structural aspects (Barr 2013).

3.2. *From estimating to incorporating connectivity in marine protected area design*

Effective integration of connectivity into MPA processes requires first the ability to estimate connectivity-related indicators. These indicators reflect the movement of organisms, genes, and materials across marine environments and are essential for assessing ecological coherence and functional linkages within MPA networks. Common tools for estimating connectivity include demographic tagging (e.g., acoustic or satellite tagging of fish to track movement pathways including transboundary movement), genetic analyses (to infer gene flow and population connectivity), biophysical oceanographic models (to simulate larval dispersal), and habitat-based surrogates (e.g., using habitat continuity) (Balbar and Metaxas, 2019; Riginos and Beger, 2022; Tanner et al., 2025). Biotelemetry has also become a cost-effective method to track marine animal movements and inform management actions (Dhellemmes et al. 2023; Thorburn et al. 2024; Hussey et al. 2015).

Each method links to different indicators: for example, tagging data can provide spatially explicit evidence of adult or juvenile movement corridors; genetic structure metrics can serve as indicators of reproductive isolation; and larval dispersal kernels derived from oceanographic models can be used to identify areas of production and retention of larvae essential for understanding metapopulation dynamic. However, these approaches vary in complexity and feasibility. Biophysical models offer detailed simulations but are resource-intensive; genetic methods provide long-term insights but may mask recent demographic changes; and habitat surrogates are scalable but risk oversimplification without validation (Jahnke and Jonsson, 2022; Gatti et al., 2021; Tyler and Kowalewski, 2017).

Selecting appropriate connectivity indicators therefore depends on management goals, spatial scale, and data availability, and ideally combines multiple methods to produce more robust connectivity assessments. Despite the variety of methods, their application remains constrained by data availability, methodological uncertainties, and challenges in interpreting outputs for management (Gardner et al., 2024). Estimating connectivity is not an end, it is a prerequisite for guiding spatial planning, understanding ecological linkages, and assessing the functionality of MPA networks. Without credible estimates, efforts to incorporate connectivity risk being tokenistic or misdirected. Thus, the focus must shift toward pragmatic, integrative approaches that combine multiple methods and deliver actionable insights for practitioners.

Once reliable estimates of connectivity are available, they can inform MPA design and evaluation in more systematic ways. Balbar and Metaxas (2019) propose a four-part framework: (1) setting clear conservation objectives; (2) identifying relevant biological and physical data; (3) interpreting connectivity outputs through tools such as connectivity matrices and dispersal kernels; and (4) incorporating feedback through ongoing assessment. This structure remains widely cited, but its success hinges on ensuring that the methods used for estimating connectivity align with management goals and scales. For example, dispersal distances derived from biophysical models can guide the spacing of MPAs to promote larval recruitment (Abecasis et al., 2023; Assis et al., 2021), while genetic estimates of gene flow can validate whether populations remain linked across protected areas (Berkström et al., 2022; Friesen et al., 2019). Network analysis of connectivity data can identify key "nodes" for protection and suggest priority areas for steppingstones or corridors. However, meaningful application requires ongoing dialogue between scientists and managers to translate these complex metrics into practical decisions (Van Diggelen et al., 2022). Post-hoc evaluation of implemented designs, using the same methods applied during planning, further supports adaptive management and long-term MPA functionality. Transboundary governance incorporating connectivity into MPAs is not simply a design challenge, it is a dynamic, data-informed process that depends on robust estimation methods and sustained capacity to interpret and respond to ecological linkages over time.

4. Marine protected areas need to be temporally adaptable

Temporal adaptability of MPAs involves adjusting their protection measures and boundaries in response to temporal changes such as seasonal variations, climate change impacts, and migratory patterns of marine species (Mills et al., 2015; D'Aloia et al., 2019). This adaptability ensures that MPAs can remain effective in conserving marine biodiversity and ecosystems despite the shifting conditions and pressures they face (Schmidt et al., 2022). Enhancing the temporal adaptability of MPAs can involve supporting seasonal adjustments, climate change responses, general ecosystem monitoring, or responding to organism movement and changes in species distribution (Fig. 1c).

4.1. Sustained site monitoring and data collection

Effective temporally adaptable MPAs need continual data collection to track marine ecosystem responses to environmental changes (Hopkins et al., 2016). This process needs two things: long-term monitoring programs and technological integration (Perera-Valderrama et al., 2020).

Establishing and maintaining long-term monitoring programs is key for collecting data that can be actioned for MPA adaptive management (Addison et al., 2015). These programs can track many ecological and environmental parameters, like species populations, habitat conditions, water quality, and climate variables (Wang et al., 2020; Melo-Merino et al., 2020). Long-term data allow practitioners to establish baselines and trends, crucial for understanding ecosystem variability driven by natural processes and human activities (Perera-Valderrama et al., 2020; Cvitanovic et al., 2014). Continuous records from long-term monitoring can reveal shifts in species distributions, changes in breeding patterns, or the emergence of new threats like invasive species, enabling more informed and proactive management decisions (Ban et al., 2017).

Accurate and consistent data collection is central to using functional indicators effectively (Dunham et al., 2020). Methods, like scientific surveys, remote sensing, and automated data collection systems, ensure high-quality data. However, in practice it is challenging to establish and maintain long-term monitoring. For example, a study on Mediterranean MPAs found only 5 % of surveyed MPAs had monitoring programs > 10 years, and most MPAs had inconsistent sampling approaches which limit long-term understanding of sites (Giakoumi et al., 2024). Standardized protocols are needed for data transferability and compatibility between sampling periods and locations. Long-term datasets that can detect environmental trends support management decisions (Hayes et al., 2019).

Technology can enhance MPA temporal adaptability through tools for gathering real-time data like species movement and oceanographic variables (Kachelriess et al., 2014; Appolloni et al., 2020). Remote sensing and satellite imaging can enable monitoring of large-scale environmental conditions, including sea surface temperatures, chlorophyll concentrations, and ocean currents, which are crucial for understanding broader ecological changes (Wang et al., 2020). Satellite imaging provides regional perspectives which can aid assessing habitat changes over time (LaRue et al., 2022). In addition to these large-scale tools, alternative monitoring approaches can provide finer-scale biological insights. For example, Dawson et al. (2024) used otolith microchemistry to assess recruitment patterns of European sea bass (*Dicentrarchus labrax)* in northerly UK estuaries, revealing a mismatch between spawning periods and fisheries closures. Such methods can be integrated into MPA monitoring frameworks to detect temporal mismatches between species life-history events and management measures. Combining these technologies into MPA processes can make data collection more efficient and comprehensive, supporting effective responses to environmental changes.

4.2. Understanding ecological patterns and trends

Operationalizing ecological and environmental data to support temporally adaptable MPAs involves using data trends to inform and adjust MPA processes. This requires understanding current, projected, real-time and historical data to gauge and respond to marine ecosystem changes.

Following data collection, patterns and trends can be identified and fed into MPA operational management (Fox et al., 2014). With statistical and modeling techniques, MPA practitioners can identify patterns and trends over time. For example, a consistent rise in sea temperatures or an increase in the abundance of an invasive organism might indicate potential marine ecosystem shifts (McWhorter et al., 2022). Trends in species population data, like a declining predator population, could suggest overfishing, declines in herbivore prey, or habitat loss (Edgar et al., 2014; Davis et al., 2018). Understanding predator–prey dynamics and other relationships with integrated data helps anticipate and respond to ecosystem changes, promoting marine ecosystem health in MPAs. Predictive modeling, by incorporating process-based indicator data, aids in simulating future scenarios and assessing management strategy outcomes (Fulton et al., 2015).Such insights provide essential evidence to design new conservation measures and review of current management measures, protection levels, or zonation. For example, Lyme Bay in the UK hosts a highly protected MPA, this site has been updated and expanded as more information and novel monitoring and data integration strategies have been developed (Renn et al., 2024). Data collected using techniques including towed video data and baited surveys was fed back to stakeholders allowing for the evolution of management plans of the MPA. These helped turn an area that was previously voluntarily closed to fishing, into a formal MPA.

Effective communication and collaboration are central for integrating ecological and environmental trend data. MPA practitioners should work closely with scientists, local communities, and stakeholders to interpret data trends accurately to support pragmatic management strategies (Gerhardinger et al., 2009).

4.3. Climate and human induced pressures

Temporally adaptable MPAs can respond to the unpredictable impacts of climate change and human pressures. Many MPAs are designed to restore ecosystems to a historical point or maintain an ecological baseline, often neglecting future impacts such as climate change (Schmidt et al., 2022), or accounting for shifting baselines (Plumeridge and Roberts, 2017). But management plans and measures can be updated to enhance MPA resilience.

Exploring “what if” scenarios can aid MPA adaptability. For example, continued coastal development could hinder biodiversity, while stringent pollution controls might foster rapid marine life recovery (Duarte et al., 2020). Widespread sustainable fishing could enhance fish populations, supporting conservation and local economies (Edgar et al., 2014). These scenarios emphasize the need for adaptive, forward-thinking management strategies that address shifting human activities and environmental conditions (Predragovic et al., 2024).

Real-time environmental monitoring systems help MPA temporal adaptability (Wang et al., 2020; Wilson et al., 2025). Climate models and forecasting tools also simulate future climate scenarios and inform adaptive MPA management strategies (Abe et al., 2021). Incorporating climate projections allows decision-makers to design resilient strategies, such as dynamic MPA boundaries, ensuring effective protection efforts despite environmental changes. These climate-resilient areas, such as thermal refugia or biologically diverse zones less exposed to warming, can be managed within MPAs through adaptive zoning, targeted protection, and long-term monitoring to safeguard their role as buffers against climate impacts (Hoppit et al., 2022). Additionally, data can help identify hotspots where marine ecosystems are particularly vulnerable to combined climate and human-induced stressors (Simeoni et al., 2023).

5. Improving the use of local and traditional knowledge

Most of our discussion has focused on scientific data supporting MPA processes. This focus is a top-down data driven approach because it involves high level individuals in MPAs processes defining goals, strategies, and processes when are then imposed into conservation action. Effective MPAs require bottom-up participatory approaches in parallel with top-down ones to complement and support each other (Jones 2012). Central to bottom-up participatory approaches for MPAs are local communities and individuals engaging, sharing their insights and knowledge to create better outcomes for the MPAs and supporting stakeholder needs (Gaymer et al., 2014) (Fig. 1d).

5.1. Supporting scientific data with local knowledge

Combining scientific, local and traditional knowledge is essential to integrate ecological and environmental data into MPA processes (Katsanevakis et al., 2020). This integration improves marine ecosystem understanding, data quality, and promotes better management practices (Boubekri et al., 2023). Scientific data is often spatial and temporal limited, particularly in less studied or remote marine regions (Ramírez et al., 2022). Research collaborations between institutions and citizen science programs have been shown to aid marine data collection (van der Velde et al., 2017), and historical and local expert knowledge can supplement MPA processes (Boubekri et al., 2023).

Local and traditional knowledge, acquired through generations, fills these gaps by offering context-specific information that scientific methods cannot emulate (Cebrián-Piqueras et al., 2020). This knowledge includes valuable insights on historical ecosystem changes, local environmental patterns, and species behavior. For example, local fishers can provide accounts of fish spawning seasons, migration routes, and fishing grounds which are key to developing MPA boundaries and regulations. Incorporating this knowledge allows MPA practitioners to create management strategies more aligned with local socio-cultural and ecological contexts, aiding compliance and legitimacy with local communities (Djosetro and Behagel, 2024).

Integrating scientific and local knowledge effectively requires collaboration respecting both sources of knowledge (Hill et al., 2020). This can involve co-management efforts where local experts, stakeholders, and scientists all participate in collecting data, analysis, and decision-making processes (Horta e Costa et al., 2022; Piñeiro-Corbeira et al. 2022). Co-management supports mutual learning and trust, helping MPA strategies be locally relevant and scientifically sound (Masud et al., 2022). Community workshops like participatory mapping exercises can gather local knowledge to validate scientific data (Reed et al., 2008).

5.2. Stakeholder engagement

Engaging stakeholders ensures that the perspectives, knowledge, and needs of relevant parties, like local communities, are considered in MPA planning and management (Di Franco et al., 2020). This inclusive approach builds a sense of ownership and responsibility among stakeholders, resulting in more beneficial MPA outcomes (Artis et al., 2020), such as minimized stakeholder conflicts which benefit implementation and compliance. For example, in the MedPAN network of Mediterranean MPAs, co-management with local fishers has led to greater compliance with no-take zones and improved ecological outcomes (Claudet et al., 2010).

Stakeholder engagement promotes legitimacy and acceptance of MPAs (Dehens and Fanning, 2018). Decision-making processes with stakeholders improve acceptance of MPA management practices and regulations (Katikiro et al., 2021). For communities whose livelihoods and cultural practices are impacted by MPAs, this is key. Inclusive participation reduces conflicts and builds trust, as stakeholders feel their voices and concerns are addressed and considered (Bennett et al., 2021). Involving local fishers in designating MPA boundaries and establishing no-take zones helps balance socio-economic needs and conservation aims, meaning MPAs contribute to sustainable development and conservation.

Adaptive management is aided by stakeholder engagement, vital for the dynamic and complex nature of marine ecosystems (Eaton et al., 2021). Continuous stakeholder collaboration and dialogue enables MPA practitioners to gather local observations plus real-time feedback, that can complement scientific monitoring to adjust management practices. An adaptive approach ensures effective MPAs to respond to environmental changes and emerging challenges.

5.3. Capacity building

Capacity building plays a pivotal role in this integration by enhancing the skills, knowledge, and resources of local communities and stakeholders. Key to capacity building is education and training. By providing local communities with training on scientific methods, data collection, and conservation practices, they are empowered to more actively participate in MPA processes (O'Connor et al., 2024). Training programs can include species identification, habitat monitoring, GPS and data logging. Equipping local stakeholders with these skills enables their contribution to data collection that complements scientific research, fostering a holistic understanding of marine ecosystems. Local fishers can systematically record observations on fish populations and environmental conditions, offering real-time data that aids ecological assessments and MPA management decisions.

Capacity building also supports mutual learning between local communities and scientists. This mutual exchange of knowledge promotes collaboration, helping local knowledge be better integrated into MPA processes (Lucrezi et al., 2019). Collaborative research projects, with local experts and scientists working together to address specific conservation challenges, build mutual and better understanding of a topic (Paredes et al., 2019).

Providing technical support and resources is a key component of capacity building. Local communities need to access equipment, financial resources, and technical guidance to effectively participate in MPA processes (Di Franco et al., 2020). Ensuring resources are available helps to sustain community engagement in projects and furthers integration of local knowledge. Funding can purchase necessary equipment, support monitoring programs, and aid training. Establishing supportive networks offering guidance and technical assistance can assist local communities navigate processes and effectively contribute to MPA governance (Collier 2020).

Supporting local governance structures to build institutional capacity also helps. Strengthening local institutions, like fisheries cooperatives, enables them to more actively participate in MPA processes (Bennett et al., 2021). Organizational development programs that enhance leadership, management, and advocacy skills are instrumental in this process. Strong local institutions can effectively represent community interests, advocate for the incorporation of local knowledge, helping management decisions align with sustainable practice and local priorities.

6. Conclusions

The effective integration of ecological and environmental data for MPA processes requires an approach that integrates various indicators, connectivity considerations, adaptability mechanisms, and the inclusion of local and traditional knowledge. By employing functional, process, and ecosystem-based indicators, we can gain comprehensive insights into MPA health and efficacy. Recognizing and estimating connectivity ensures that MPAs are not spatially restrictive, supporting resilience and ecological coherence across broader marine settings. Temporal adaptability, aided by sustained site monitoring, data collection, and an understanding of ecological patterns and trends, is essential to address the dynamic nature of marine ecosystems and combining climate change and human activity pressures. Improving data integration and leveraging local and traditional knowledge through stakeholder engagement and capacity building can enrich further MPA processes. These combined strategies can enhance the sustainability and effectiveness of MPAs, ensuring they fulfill their crucial role in marine conservation.

CRediT authorship contribution statement

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Declaration of competing interest

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

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Data availability

No data was used for the research described in the article.

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