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The next ten steps for integrating Marine Functional Connectivity (MFC) into policy, planning, and management

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A B S T R A C T

Given the complex nature of Marine Functional Connectivity (MFC) science, MFC experts sit in a unique position to lead discussions on strategies for ocean planning and management that would turn "paper parks" into effective conservation areas. This includes addressing the cumulative pressures from human activities, and the next steps to be taken by planners, managers, and policymakers to ensure efficient marine conservation. This study presents expert-recommended actions for effectively incorporating MFC into marine policy and planning. It follows multiple calls to assess MFC influence on meeting global 2030 marine conservation goals. A total of 99 MFC experts participated in the study, all members of the 2022-2024 COST Action "Unifying Approaches to Marine Connectivity for Improved Resource Management for the Seas". These experts suggested and ranked the ten emerging action categories presented here as priorities, or 'Ten Next Steps', for supporting

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MFC data collection and its integration into current conservation and sustainable development efforts. The results support the following for effective marine conservation planning and management: 1. Connecting MFC efforts to existing conservation efforts; 2. More collaborative and accessible science-stakeholder platforms; 4. Encouraging interdisciplinary approaches and training; and 5. "translating" complex MFC data into accessible MFC-informed maps, reports, and methods, including operational frameworks and indicators.

1. Introduction

Marine Functional Connectivity (MFC) refers to the dynamic spatial exchange of biomass, individuals, genes, and energy through the collective lifetime movements of marine organisms (Darnaude et al., 2026). Comprehensive knowledge of MFC is crucial for understanding the distribution and resilience of marine biodiversity, as well as the structure and functioning of marine ecosystems (Lamberti et al., 2010; Marcos et al., 2021). MFC plays a key role in maintaining, and in some cases restoring, the health of marine environments, especially as they face challenges from climate change and human activities (Massol et al., 2017; Carr et al., 2017; Lenoir et al., 2020; Cannizzo et al., 2021).

Global targets to protect the ocean by area-based management tool (ABMTs) have previously been set at 10% (Grorud-Colvert et al., 2021). The UN Convention on Biological Diversity adopted the Kunming-Montreal Global Biodiversity Framework in 2022, calling for 30% protection of marine areas by 2030 (CBD, 2022). In Europe, these global targets are complemented with the regional seas conventions such as the Barcelona Convention, the Black Sea Convention, OSPAR and HELCOM, also committed to the 30% targets. European ABMTs are further supported by the non-legally binding European Biodiversity Strategy for 2030, which aims at 30% coverage of marine protected areas (MPAs) of which 10% are strictly protected (Aminian-Biquet et al., 2024; Stephenson et al., 2025). In practice, the European environmental legislation led to the designation of 11.4% of its waters as MPAs as of 2022. The effectiveness of these MPAs in maintaining and restoring biodiversity targets has been questioned, and guidelines to improve their design, implementation, assessment, and management have been issued and applied in European Union MPAs (Aminian-Biquet et al., 2024; Sullivan-Stack et al., 2024; Ulaş et al., 2025).

By advancing MFC knowledge, researchers aim to better predict and help mitigate the impacts of global change on marine resources and ecosystem services and identify operational adaptation measures in which marine connectivity plays an important role. However, for many years, most of the knowledge pertaining to marine connectivity was derived from land-based methods and conceptual approaches. Only recently have comprehensive and interdisciplinary efforts emerged to develop an integrative, unified framework specifically tailored to marine-based functional connectivity (Darnaude et al., 2026; Warmuth et al., 2025).

Recent technological and methodological advances have transformed the way MFC data are collected and analyzed, requiring a reassessment of how MFC can and should be incorporated into marine planning and policy (Warmuth et al., 2024; Preston et al., 2025; Rieder et al., 2025; Darnaude et al., 2026). Indeed, the following advancements have significantly improved the effectiveness and precision of studying MFC providing complementary information across spatial and temporal scales (Tanner et al., 2016; Sturrock and Tanner): enhanced precision of genetic analysis (McGill et al., 2023); refined biophysical modelling (Sciascia et al., 2022); more efficient electronic tagging and tracking of marine organisms (Welch et al., 2024); improved isotopic methods to reconstruct dietary patterns and habitat use (Silberberger et al., 2024); increased availability of packages for mapping and spatial analyses using remote sensing and satellite data (Gamoyo et al., 2019); integrating ecological network analysis and molecular tools such as environmental DNA for monitoring (Beng et al., 2025). By generating spatially and temporally explicit, measurable connectivity metrics, these emerging methods can be used to test management options and anticipate change, and this shifts MFC from a largely conceptual design principle to an operational input, requiring a reassessment of how connectivity objectives, indicators and adaptive decision rules are embedded in conservation and development efforts (Beger et al., 2022; Krueck et al., 2022).

The need to reassess how MFC considerations and metrics can and should be integrated into marine and coastal policy, planning, and management, is also highlighted by the need to address increasing anthropogenic pressures on marine ecosystems, such offshore infrastructure (e.g. windfarms), shipping, overfishing, and deep sea mining, combined with global effects of climate change, invasive species, and biodiversity loss (Darnaude et al., 2026; Warmuth et al., 2024, 2025). This study aims to provide concrete, specific, and actionable recommendations for next steps in MFC incorporation, i.e., advancing MFC-informed marine conservation and management, reviewing the resulting recommendations in light of existing MFC literature and efforts. Towards this, we surveyed MFC experts through a two-phased, mixed-method expert survey, in order to identify opportunities to ground current and future MFC knowledge into conservation policy, planning, and management.

2. Method

2.1. Two-phase expert survey

The two-phase survey was designed to gather knowledge from a panel of experts via multiple rounds of anonymous questionnaires, with the aim of informing policy and applied decision-making. After the first round, a summary of the group responses was shared (maintaining participant anonymity), and the expert group was asked to grade the resulting action items. This methos, inspired by multi-phased Delphi surveys, which include multiple rounds and often orient towards the future, enabled a uniquely systematic and efficient internal peer-review process performed by experts during the data collection phase (Barrett and Heale, 2020). This methodology, of multiple rounds, collective analysis, and anonymous feedback, supports reflection, refined judgment, anonymity, reduction of bias, and diverse perspectives, thereby promoting a more inclusive and holistic approach to complicated scientific questions (Scolozzi and Geneletti, 2012, Mukherjee et al., 2015; Barrett and Heale, 2020; Niederberger and Köberich, 2021).

2.2. Procedure

In round 1, participants were asked to answer three open questions about MFC integration. In round 2, participants received a summary of all the answers in the form of proposed action items, and were asked to grade their importance, between 0 and 3.

Round 1 of this study was a survey circulated among the ca. 300 members of the EU-sponsored and UN-supported COST Action CA19107 SEA-UNICORN "Unifying Approaches to Marine Connectivity for Improved Resource Management for the Seas", an international network of MFC experts (www.sea-unicorn.com). SEA-UNICORN members were invited via email to fill out a Google Form, answering the following questions:

1. What, in your opinion, are the next steps to raise awareness of MFC and to integrate MFC data and considerations in marine planning, policy, and management considerations?

2. What, in your opinion, is/are the main current barrier(s) to incorporating MFC in policy, planning, and management, and what needs to happen to overcome them?
3. What, in your opinion, will be the main challenge(s) for marine planning, policy, and management in 10-15 years, and what can be done to anticipate them and begin to address them in the near future?

The answers were then thematically analyzed using ATLAS.ti software, which allows researchers to tag and count repeating ideas ("themes") across participant answers (Sharma, 2024). Themes mentioned by two or more experts were subsequently consolidated into a list of suggested next steps. In *Round 2,* this list was sent to all SEA-UNICORN experts as a Google Form, where they were asked to score each item on a scale from 0 (not important) to 3 (very important). SEA-UNICORN experts were allowed to score these items even if they did not fill out the first survey (See supplementary materials 1-3 for survey questions and answers. In 2023-2024, SEA-UNICORN experts from 32 countries completed Rounds 1 and 2. The sample for each round was as follows:

Round 1: **71 participants**.
Round 2: **69 participants**.
Rounds 1 + 2: **41 participants**.
Round 1 only: **30 participants**.
Round 2 only: **28 participants**.
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Total: Round 1 or 2: **99 participants**.

2.3. Data analysis

Survey responses from Round 1 were analyzed using inductive thematic analysis supported by ATLAS.ti, a Computer-Assisted Qualitative Data Analysis Software (CAQDAS) that facilitates the systematic organization, coding, retrieval, comparison, and categorization of qualitative textual data (Mastrobattista et al., 2024). In thematic analysis, researchers identify meaningful segments of text, assign descriptive codes to them (i.e., "coding" process), and subsequently examine recurring patterns among codes to develop broader thematic categories relevant to the research questions. The study followed an inductive approach, in which codes were developed from participants' responses rather than from a predefined coding framework (Fereday and Muir-Cochrane, 2006). For example, a participant might recommend "including larval dispersal pathways when identifying areas for marine protection," which could be coded as "larval dispersal," "connectivity-informed MPA design," and "incorporating MFC into spatial planning." Related codes were then compared and grouped into broader thematic patterns; for example, codes concerning "making MFC data accessible," "translating science for planners," "decision-support tools," and "communicating uncertainty" could contribute to a broader theme concerning the translation of MFC science into actionable information for decision makers.

Recurring codes were subsequently consolidated where they represented overlapping or closely related ideas, creating *themes*. Themes mentioned by more than one participant were retained as potential collective recommendations, while highly specific ideas raised by individual participants were also retained where they provided substantively distinct insights relevant to the research questions. The resulting themes were then consolidated into the list of proposed next steps presented to participants for numeric evaluation in Round 2. ATLAS.ti was used to support and document this analytical process, providing a systematic means of organizing the original responses and maintaining links between responses, codes, and resulting themes (Braun and Clarke, 2006; Mastrobattista et al., 2024). The optional ATLAS.ti AI feature was not used in the analysis.

2.4. Limitations

Participants were predominantly scientists with a background in biology and related fields such as fisheries, conservation, or marine and coastal planning. Some had extensive experience with NGOs, stakeholders, and country- or EU-level policy and planning, while others only had limited experience engaging directly with decision makers, managers, or stakeholders. Thus, we suggest that the insights gained in this study would be particularly beneficial for MFC or marine scientists and academic policy makers, as well as address how MFC science can effectively contribute to marine and coastal planning and policy more broadly. Also, due to natural attrition, some participants who participated in Round 1 did not participate in Round 2. However, once the findings of Round 1 were published among the SEA-UNICORN members in 2024, it also prompted members who did not participate in Round 1 to participate in Round 2.

3. Results

3.1. Round 1

We identified six core themes:

1. **Advocacy:** Fostering a better awareness and support for MFC integration.
2. **Collaboration:** Initiating and improving collaboration on MFC goals between scientists from different disciplines, and between scientists and policymakers.
3. **Data:** Enhancing data collection, standardization, analysis, reporting, and sharing.
4. **Tapping into existing efforts**: Connecting to and leveraging existing marine management conservation initiatives to advance MFC-informed research and decision-making.
5. **Products:** Developing new materials for facilitating MFC integration.
6. **Stakeholder engagement:** Promoting and discussing MFC with multiple and diverse stakeholders using effective stakeholder-specific strategies and platforms.

Within those themes, multiple recommended next steps emerged, which were graded for importance in Round 2. The results of both Rounds, 1 and 2, appear below in Table 1, with the left column describing the main themes extracted from the round 1 answers and the grade for importance each one received in Round 2. In the right column, we included the specific next steps proposed by the experts in Round 1 (See full Round 1 survey answers in *Supplementary Materials*).

4. Discussion

This section explores each of the ten highest-ranking priorities (established in Rounds 1 and 2), and synthesizes the existing relevant knowledge, technologies, policies, solutions, and efforts already underway, and discussing options to support their practical application.

4.1. ***Translate data*** *into* ***actionable knowledge*** *for policymakers*

The survey answers emphasized that MFC science needs to be translated into simple, decision-oriented products that demonstrate how connectivity changes actual management outcomes, including ecological, social, and economic consequences. Beyond raising awareness, scientists should provide tools, examples, visualizations, and models that answer the practical questions policymakers and managers already face. Tools to generate and process MFC data are already available (Sturrock and Tanner,; Darnaude et al., 2026), and robust theoretical (Beger et al., 2022; Fontoura et al., 2024) and methodological frameworks (Beger et al., 2010; Magris et al., 2018; Daigle et al., 2020) exist to

Table 1
Summary of recommendations – survey findings rounds 1-2.

Main Themes *(Priority/3)*	Practical Steps for MFC Experts
1. Translate data into understandable and actionable knowledge for policymakers *(2.85/3)*	1. Present MFC data and knowledge in a **simple, decision-oriented way**, rather than expecting policymakers to interpret complex connectivity analyses. 2. Identify **textbook cases and canonical examples** showing a concrete management decision with and without MFC. 3. Build more **decision-support tools** that show real and hypothetical scenarios that demonstrate incorporating vs. ignoring MFC changes and predicted outcomes. 4. Create additional **policy-specific dissemination materials**, tailored to particular audiences rather than generic outreach. 5. Use **videos, infographics, briefing notes and short reports** to explain otherwise complex modelling. 6. Include **social and economic consequences of decisions**, not only ecological. 7. Make MFC outputs compatible with existing management units and models even if this means **deliberately simplifying the underlying complexity.** 8. Use **color-coded or similarly intuitive outputs** so managers can interpret connectivity without specialist software or scientific expertise. 9. Identify the **indices currently uses** and show how much **those indices change when MFC is incorporated.** 10. Develop **models that stakeholders and project managers can actually operate**, rather than models designed primarily for researchers.
2. Promote MFC-informed MPA and MPA networks planning and management *(2.85/3)*	11. Compare **MPA/habitat-restoration scenarios with and without MFC** so policymakers can see the added value quantitatively. 12. Treat MFC as a way of assessing whether an MPA network is actually **"functioning"**, rather than merely whether protected areas exist on a map. 13. Design **connected networks rather than isolated MPAs**, including connectivity corridors and linkages among habitats. 14. Develop MPA networks that **cross national/state boundaries**, as connectivity frequently operates at larger spatial scales than governance. 15. Build **future climate change into MPA design now**, rather than designing networks around current distributions that may soon shift. 16. Put explicit references to connectivity into the **legal instruments and management documents** that MPA managers already use. 17. **Identify cases where an MPA no longer protects the habitat/species** it was designed for because connectivity and environmental conditions have changed. 18. Connect MFC with **terrestrial functional connectivity**, creating a broader network rather than treating marine connectivity as an isolated issue.
3. Connect to existing government tasks related to marine areas *(2.81/3)*	**Insert MFC into: processes governments already have**, rather than create a new standalone MFC policy process, including: 19. Existing government planning at **local, regional, national and EU levels.** 20. **Existing legal and regulatory frameworks** instead of new MFC-specific ones. 21. **Fisheries stock assessment and stock management decisions**, particularly mixed/connected stocks. 22. **Marine spatial planning (MSP).** 23. **Environmental impact assessment** and assessment of major infrastructure. 24. **Engineering design**, particularly where physical barriers disrupt connectivity. 25. **Restoration and biodiversity programs**, including existing EU/ Horizon Europe/Mission Ocean initiatives. 26. **Monitoring and evaluation of management measures.** 27. **Engineering efforts**: develop evidence at the spatial scale of actual infrastructure and translate connectivity into specific engineering design criteria, including engineered products creating selective barriers for certain species. 28. Define **model/data requirements in advance of planning processes,** specifying the information, data formats and model outputs needed to forecast species and ecosystem services.
4. Support collaboration between MFC scientists and international regulation bodies *(2.80/3)*	29. Give MFC scientists a **more proactive role in international ocean governance** 30. Present MFC directly to **regional fisheries bodies and advisory councils.** 31. Engage both the **EU/international level and individual member states**, rather than assuming influence at one level will filter down. 32. Participate directly in **intergovernmental MPA planning.** 33. Establish internationally open data and research infrastructure. 34. Use international conferences and policy congresses as **policy engagement venues**, not just academic dissemination opportunities. 35. Develop coordinated approaches across EEZs, particularly for **highly migratory stocks.** 36. Build connectivity into the **international legal instruments** and regulatory frameworks used by managers. 37. Shift from "communicating science internationally" toward **using scientists as active intermediaries in transboundary negotiations.** 38. Use **scientific diplomacy** to address transboundary connectivity where political jurisdictions do not match ecological systems. 39. **Scientific diplomacy** should be used as a mechanism for converting connectivity science into **compatible political decisions and regulations.**

(*continued on next page*)

Table 1 (*continued*)

Main Themes *(Priority/3)*	Practical Steps for MFC Experts
5. Integrate MFC into coastal management plans *(2.73/3)*	40. Make connectivity a **structural feature of coastal management**, rather than an additional scientific consideration 41. Restore **specific coastal habitats** as connectivity nodes. 42. Connect protected areas using **ecological corridors** to facilitate movement and genetic exchange. 43. Link MPA network planning to **local coastal management plans.** 44. Make MFC part of both **implementation and monitoring**, not just plan preparation. 45. **Involve stakeholders during plan development** so that the plans are more implementable and so MFC awareness spreads through the planning process. 46. Integrate **ecological, temporal and spatial connectivity tools** into management frameworks. 47. Use **existing coastal restoration projects as practical entry points for MFC**, rather than trying to insert connectivity into coastal planning as an abstract concept, i.e., *restore habitat → identify its connectivity functions → connect it to neighboring habitats/MPAs → monitor whether the network functions.*
6. Create MFC indicators that are easy to integrate, update, and monitor *(2.70/3)*	Establish an indicator system that would: 48. Identify the **key components of MFC.** 49. Identify the variables that best capture those components. 50. Prioritize variables that are **cheap/easy enough to measure repeatedly.** 51. Combine them into **standardized** MFC indicators. 52. **Standardize the underlying measurement methods** so different researchers/agencies generate comparable data. 53. Convert the results into **simple visual codes**, potentially including traffic-light/color systems. 54. Put the indicators into **GIS/spatial decision-support systems.** 55. Design them so they can be **updated and monitored routinely**, rather than requiring a new research project each time. 56. Harmonize connectivity data with **life-history, migration, phenology, abundance, production and environmental data**, using open curated databases. 57. **Visualization/software complexity itself is a barrier** so scientists providing indicators should also produce an **intuitive management interface** that mitigates underlying complexity
7. Explain the benefits/risks of addressing MFC to decision makers *(2.70/3)*	58. Quantify the **economic, health, employment and societal benefits** of applying vs. not applying MFC considerations. 59. Conduct explicit **cost-benefit analyses of MFC research and implementation.** 60. Demonstrate difference between management scenarios **with and without MFC.** 61. **Show how ignoring connectivity can create concrete risks**, such as unintended overfishing of less productive components of connected stocks. 62. Link MFC to sectors such as **Nature-Based Solutions** and new **blue-economy industries.** 63. Explain consequences in terms of **people's own circumstances**, including **social and economic impacts.** 64. Use **memorable analogies and high-profile case studies** rather than abstract explanations. 65. Quantify the **added value of MFC**: What changes in a management decision once MFC is included? What would be missed if it were excluded? An "MFC conservation guide" could catalogue those situations and synthesize how existing policy-relevant indicators change when connectivity is considered.
8. Increase collaboration of MFC scientists with nature conservation agencies *(2.69/3)*	66. Place MFC researchers in **agency working groups and planning processes.** 67. Develop standing links with **nature-conservation offices, fisheries agencies, NGOs and EU bodies.** 68. Work through **existing biodiversity/restoration initiatives**, including Horizon Europe/Mission Ocean/Life/Interreg projects. 69. Provide agencies with **short, concise, science-based products** that can be incorporated into existing governance. 70. Use **multi-stakeholder networks** as the mechanism for making science into practice. 71. Support agency staff through **training and capacity building**, not just one-off presentations. 72. Connect MFC to **nature-based solutions**, potentially making connectivity relevant to a wider conservation and investment community.
9. *Future:* Monitor and adapt to climate change impacts on MFC *(2.76/3)*	73. Move from static connectivity maps toward **dynamic, predictive connectivity management.** 74. Monitor changes in **species distributions, abundance, life-history traits and phenology.** 75. Combine distribution monitoring with **genetic/connectivity information** to anticipate demographic responses. 76. Develop **climate-smart MPA planning**, using projected rather than only current distributions. 77. Build scenarios of changing **temperatures, sea-level rise, acidification, and other anthropogenic pressures** and their effects on species interactions and ecosystem functioning. 78. Use connectivity to assess **species' capacity to adapt** to changing environmental conditions. 79. Develop management systems capable of **rapid adjustment**, rather than repeatedly reassessing static plans. 80. Combine **experimental evolution/life-history research with modelling** to understand how MFC itself changes under future environmental conditions.

(*continued on next page*)

Table 1 (*continued*)

Main Themes *(Priority/3)*	Practical Steps for MFC Experts
10. *Future:* Study and reduce the impacts of intensifying Blue Growth on MFC *(2.71/3)*	81. Use **scenario and sensitivity testing** to explore ecosystem resilience when data are incomplete. 82. Treat **connectivity itself as something that can change under climate change**, rather than merely using today's connectivity to protect today's populations. 83. Explicitly address the **mismatch in time scales**: marine ecosystems may shift faster than management systems can revise MPAs, regulations or plans. Thus, MFC-informed management needs to be **adaptive by design.** 84. Explicitly incorporate MFC into planning for **offshore renewable energy, aquaculture, tourism, fishing and other expanding uses.** 85. Use MFC to assess the **cumulative consequences of competing uses of marine space**, rather than assessing each activity independently. 86. Use scenario planning to test trade-offs among **conservation, fisheries, aquaculture, energy and other development.** 87. Assess major infrastructure projects for their potential effects on **movement of marine organisms and connectivity**, as suggested for the Istanbul Canal. 88. Address **deep-sea mining** proactively because connectivity/ecosystem impacts may be large but poorly understood. 89. For tourism, one respondent specifically proposes **restricting mass tourism and promoting "slow tourism" through small-scale interventions.** 90. Explore **co-location of uses** carefully, particularly aquaculture and renewable energy, rather than assuming co-location automatically reduces spatial conflict. 91. Develop inclusive and transparent mechanisms for resolving conflicts among **fishing, aquaculture, tourism, transport and conservation.** 92. Use MFC/Ecosystem-Based Management (EBM) modelling to test the **resilience of different development scenarios**, especially where data are incomplete.

integrate these data into management and conservation planning. However, there is still a lack of practical implementation of MFC data and knowledge into management plans (Balbar and Metaxas, 2019). Thus, raw data from *in situ* observations and model outputs must be standardized and transformed into actionable metrics, practical guidance, and tools for policymakers, practitioners, and the public (Allen et al., 2021, Darnaude et al., 2026). Ideally, stakeholders, managers, and policy makers should be involved early in the process, so that the science produced can be directly applied Weichselgartner and Kasperson (2010).

Generalizability, simplicity, and uniformity present challenges when translating spatiotemporally complex MFC data into understandable and actionable knowledge for policymakers. The development of policy-specific indicators that synthesize complex connectivity information is key (Metaxas et al., 2024), particularly under current regulatory contexts where MFC frameworks are often lacking. Promoting the interaction between data and modelling can also help generate actionable knowledge by simulating the effects of different management options and providing quantitative results (Warmuth et al., 2024, 2025).

Collaborative, integrated and uniform management is required across governmental levels to achieve MFC objectives, as MFC operates at multiple spatial and temporal scales that must be considered within policy jurisdictions to support ecologically relevant processes. For example, the effective conservation of migratory species may depend on trans-municipal, district, province, and national collaboration (Mazor et al., 2016). However, such coordination is rarely implemented, since transboundary work is seen at times as a politically complicated endeavor with few gains and, numerous unforeseen political and socio-economic trade-offs (Katsanevakis et al., 2020). There is also a need to address and resolve real capacity gaps in data collection, management, standardization, and sharing between jurisdictions (Maureaud et al., 2021; Tanner et al., 2016).

4.2. *Promote MFC-informed MPA and MPA networks planning and management*

Survey answers conclude that MFC should be incorporated into the design, evaluation, and adaptive management of MPA networks, including networks that cross political boundaries. Importantly, connectivity could be used not only to design networks but also to assess whether existing MPAs are actually functioning ecologically and whether they remain effective as conditions change. MPAs have proven to be an effective way to provide refuge for maintaining the genetic diversity of exploited populations (Pérez-Ruzafa et al., 2006) and to preserve the functional structure of complex ecosystems (García-Charton et al., 2008). However, not only is the overall area protected important, but also the quality and configuration of habitats within the network, and the governance of whatever protective measures were put in place. Many MPA systems were created without directly addressing functional connectivity, a crucial aspect of their fitness for purpose (Gill et al., 2017; Fraschetti et al., 2018).

Specific MFC criteria should be included in future MPA and MPA network planning. Currently, conservation efforts often prioritize spatial coverage over ecological function. Such initiatives often fail to account for the dynamic exchanges of fish larvae, migratory species, and even microbial communities (Allgayer et al., 2024), risking fragmentation and reduced ecological resilience (Beger et al., 2022). Hydrodynamic models, genetic connectivity assessments, and telemetry data are increasingly being used to inform MPA planning, ensuring that conservation measures extend beyond static boundaries and align with species movement and oceanographic patterns (Darnaude et al., 2022). Life-history traits should also be considered, including the protection of spawning sites or of key habitats along major oceanic currents to enhance dispersal and genetic exchange (Henriksson et al., 2025). Some MPAs also need to account for the varying dispersal patterns of multiple species, while all MPAs should consider future changes in temperature and oceanographic patterns relating to climate change (White et al., 2010; Cristiani et al., 2024).

Monitoring and adapting, new MFC data could inform how existing MPAs need to be updated and adapted. Rising ocean temperatures, habitat degradation, and changing animal migration routes are altering functional linkages between protected areas (Gill et al., 2025). Since climate refugia are not always stationary, their spatial dimensions and dynamics can also change (Lezama-Ochoa et al., 2025; Coleman et al., 2017). In response, dynamic MPAs - capable of adjusting boundaries in real-time based on ecological data - have been proposed as a solution for addressing shifting connectivity pathways (Muenzel et al., 2023). MFC scientists should also address key functional groups and species that could affect mitigation efforts, such as grazers and detritivores on coral reefs that perform ecosystem functions aiding habitat recovery after disturbances such as storms or coral bleaching (Brandl et al., 2019; Cinner et al., 2019; Graham et al., 2024; Warmuth et al., 2024).

The spatial and temporal scales at which connectivity occurs are

important when considering the fluxes across MPA networks. Connectivity scales depend on the phases of the life cycle considered, life histories, primary producer lineage and structural connectivity. Structural connectivity includes the continuity and fragmentation of static habitats as well as the mesoscale dynamics of currents and the pelagic habitats (Palumbi, 2004; Manel et al., 2019; Preston et al., 2025). Temporal scales are also diverse, with long-distance dispersal affecting genetic structure over evolutionary time scales (Manel et al., 2019), while connectivity influences on population dynamics or ecosystem function act on much shorter timescales. Protecting processes at larger spatio-temporal scales may require larger MPAs or additional MPA networks (Coleman et al., 2017).

4.3. Connect to existing government tasks related to marine areas

The survey found that creating entirely new MFC-specific governance processes is excessive if MFC can be integrated into existing government activities such as marine spatial planning, environmental assessments, restoration, fisheries management, and infrastructure planning. This would make MFC directly relevant to decisions governments already make and create practical pathways for its implementation. Indeed, effective management of MFC will require expanded governmental capacity. Without enhanced institutional frameworks and intergovernmental coordination, marine connectivity goals will remain challenging to achieve (Beger et al., 2022). Increased transboundary collaboration between local and national organizations as well as global governance bodies, will be necessary to adopt effective management strategies based on MFC, requiring integrated and adaptive ocean and land-sea regulation, and harmonized and standardized supranational frameworks (Cannizzo et al., 2021; Muller-Karger et al., 2024).

Global and European frameworks aim to protect 30% of marine areas by 2030 (CBD, 2022). However, recent European designation stands at only 11.4%, and the effectiveness of these MPAs, in Europe and beyond, has been questioned (Ulaş et al., 2025). *The Natura 2000 MPA network* in Europe, which includes ~12% of territorial waters and ~4000 sites, is intended to be part of a network of European protected areas. However, instead of a transboundary, systematic approach, individual European member states have predominantly designated and implemented MPAs independently in their own national waters, albeit with some transnational collaboration in certain cases. This national implementation of European legislation does not adequately account for regional connectivity patterns this led to a downgrade of the ecological coherence of the Natura 2000 network as requested in Articles 3 and 10 in the Habitats Directive (Mazaris et al., 2017) and Article 13(4) of the Marine Strategy Framework Directive (Katsanevakis et al., 2020).

4.4. Collaboration of MFC scientists with international regulation bodies

The survey indicates that the cross-border nature of marine connectivity means that MFC scientists need to engage with international and regional regulatory institutions, fisheries organizations, and intergovernmental planning processes of MPAs and other Area-Based Management Tool design. Scientific diplomacy, open international data infrastructure, and participation in policy forums could translate transboundary connectivity science into coordinated governance. Collaboration between MFC scientists and regulation bodies is necessary for MPA design, fisheries management practices, and climate change mitigation strategies, thereby supporting sustainable ocean governance (Palumbi, 2003; Beger et al., 2010; Selkoe et al., 2016).

Addressing organizational complexity is a primary challenge for international collaboration. The push for expansion and monitoring of MPAs globally will require effective cross-border collaboration between MFC scientists and regulatory bodies (Darnaude et al., 2026). By providing clear MFC indicators, scientists can assist decision-makers to design more effective MPAs, recognizing that these indicators and the underlying models can be complex for diverse decision-makers to interpret and apply (Berglund et al., 2012; Lagabrielle et al., 2014). An alternative is to present key elements such as species or habitat distribution, animal movement patterns and oceanographic processes through decision trees and maps that are more accessible to decision makers (Smith and Metaxas, 2018). When channels of communication between international regulation bodies are unavailable, it is up to scientists to translate the underpinning scientific evidence and start conversations.

MFC collaboration can encourage adjacent states to collaborate and synergize for more effective results. While formal enforcement of regulation is ultimately only applied at national or sub-national level, international or supranational efforts can provide coordination, as well as geopolitical and professional peer pressure. As with most international efforts, any inherent mandate is often undermined by the lack of enforcement tools and legal backup (Mackelworth et al., 2019). Enhancing and facilitating interaction among scientists, managers, stakeholders and decision-makers remains a key challenge to balance MFC data integration with other management goals (Chamberlain et al., 2022). Large scale data sharing schemes include IOC GOOS/OBIS efforts for data sharing and interoperability, and big databases for species movement and distribution (Darnaude et al., 2026). Scientific cooperation has a role to play not only in science diplomacy, but also in other types of "soft" diplomacy between countries, many of which collaborate infrequently or where there has been tension surrounding marine disputes. Joint scientific initiatives can encourage other transboundary collaborations, such as regional monitoring, data sharing, collaborative fisheries management, and even transboundary marine parks, which provide stability in regions of shared or adjacent marine ecosystems and beyond (Teff-Seker et al., 2020).

4.5. Connect MFC to coastal management plans

The survey answers suggest that MFC can be incorporated into coastal management through concrete activities such as habitat restoration, MPA networks, and ecological corridors that facilitate species movement and genetic exchange. Stakeholder involvement is particularly important for ensuring that connectivity considerations are incorporated into plans and successfully implemented. Thus, connecting coastal conservation and marine conservation efforts requires consideration of trans-realm MFC between land and sea (Beger et al., 2010; Tulloch et al., 2016). Trans-realm habitats act as functional connectivity nodes linking offshore and nearshore areas and populations (Bishop et al., 2017). Degradation or loss of coastal habitats, often driven by land-based stressors like deforestation, urbanization, and pollution (Gove et al., 2023), can propagate connectivity failures beyond coastal zones (Treml et al., 2015).

Coastal development impacts MFC by altering the physical, chemical and biological pathways that guide connectivity across the land-sea interface, fragmenting habitats and altering species distributions. It can simultaneously reduce functional connectivity for native assemblages while enhancing MFC for invasive or disturbance-tolerant species (Bishop et al., 2017). Anthropogenic pollution and runoff drive eutrophication and hypoxia (de Mutsert et al., 2025), mariculture and aquaculture facilities may lead to genetic introgression via escapees (San Román et al., 2025), dredging and other coastline transformations that are known to alter marine hydrodynamics, turbidity regimes and salinities (Wenger et al., 2017). MFC researchers, as well as conservation managers, should also address the MFC impacts from land-based water management activities (Prunier et al., 2020; Haas et al., 2021; Zarri et al., 2022; He et al., 2024; Poff and Matthews, 2013; Poff, 2018; Flecker et al., 2022).

Integrated coastal zone management (ICZM) and ecosystem-based management approaches attempt to address the dynamic interface where the ocean meets the land, and bridge the gap between marine and terrestrial research (Domínguez-Tejo et al., 2016). The integration of MFC into coastal management requires a structured, spatially explicit

approach that considers biotic and abiotic drivers of connectivity alongside socio-economic and governance considerations. In the context of the European Union, ICZM has not gained strong traction as member states opposed direct EU influence on land-based planning. The European Parliament and Council only agreed to recommend that member states adopt an ICZM approach in May 2002 (European Commission, 2002), but further implementation is required to reach MFC integration goals (Tocco et al., 2024; Gladstone-Gallagher et al., 2022).

Solutions to resolve these challenges require the integration of multi-scale MFC models into coastal governance frameworks, ensuring that conservation efforts extend beyond isolated patches to account for broader seascape connectivity (Berkström et al., 2022; Darnaude et al., 2026). Integrative strategies, alongside adaptive governance structures that integrate local ecological knowledge, can reinforce MFC-informed coastal planning, ensuring that conservation policies remain robust and adaptable in the face of ongoing environmental shifts (Purvis et al., 2019).

4.6. Create MFC indicators that are easy to integrate, update, and monitor

The study participants proposed a process for developing and operationalizing MFC metrics: (1) identify the components of MFC, (2) identify the variables that capture them, (3) select variables that are feasible to measure repeatedly, (4) standardize both indicators and measurement methods, (5) integrate them with life-history and environmental information, and (6) make the resulting indicators spatially explicit and routinely useable. This aligns with the argument that indicators need to be fit-for-purpose, feasible to collect over time, and capable of informing management (Muhl et al., 2022).

The specific indicators and data dimensions mentioned by participants in this study measure phenology, abundance, production, migration, life-history, habitat use, environmental conditions, spatial connectivity, and repeated monitoring. However, participants' suggestions generally stopped short of specifying concrete quantitative metrics, but rather measuring habitat quality/resistance, movement/corridors, network structure, recruitment/source-sink relationships, and marine-coastal transitions more broadly. While participants identified a *process* for developing and operationalizing MFC metrics, their recommendations did not include an exhaustive or even comprehensive list of recommended indicators, nor specified quantitative thresholds, decision rules, or procedures through which certain indicator values would trigger specific management actions. These findings should therefore be understood as identifying priorities and requirements for making MFC more applicable to decision-making, rather than as providing a validated operational framework for connectivity-informed conservation decisions.

MFC indicators suggested in recent marine connectivity studies, include: (a) species-specific movement and connectivity rates, which show whether organisms actually move between key habitats; (b) source-sink and recruitment connectivity, indicating where individuals originate and how populations contribute to one another demographically (Gardner et al., 2024); (c) habitat suitability and ecological resistance, which identify areas that facilitate or impede movement and provide the basis for modelling functional pathways; (d) functional corridors and pathways that reveal important routes, bottlenecks, and stepping-stone habitats maintaining connectivity; (e) network-level connectivity measures, particularly the Probability of Connectivity (PC) and Integral Index of Connectivity (IIC), which assess how well habitat or MPA networks function as a whole (Chen et al., 2024); and (f) marine-coastal connectivity across life stages, which captures connections among offshore, coastal, intertidal, estuarine, and other habitats essential for completing species' life cycles (Gardner et al., 2024; Chen et al., 2024). Additionally, inferring self-recruitment and larval or local retention can provide complementary measures of local population maintenance and dispersal, allowing characterization of source-sink populations and the strength of linkages between them (Lett et al., 2015, 2017). Modelling trophic connectivity provides another dimension for assessing quantitative MFC by quantifying spatial flows of matter, energy, nutrients, and biomass through food webs (Darnaude et al., 2026). To capture temporal connectivity, occurrence, flux, and frequency should also be considered, as these metrics provide information not only on where connections occur, but also on their strength, frequency, and persistence through time (Clavel-Henry et al., 2024).

Recent reviews provide a useful framework for organizing these indicators into models. Keeley et al. (2021) distinguished between structural, species-specific, multi-state, and observed functional connectivity metrics, highlighting indicators such as IIC, PC, Equivalent Connected Area (ECA), metapopulation capacity, least-cost distance, effective resistance, current-flow metrics, and genetic connectivity as appropriate for different conservation and monitoring objectives. Wood et al. (2022) extended this perspective to multispecies connectivity, identifying PC, IIC, betweenness and degree centrality, least-cost pathways, and circuit-theory metrics among the approaches used in multispecies connectivity analyses, while suggesting metapopulation capacity as a potential metric for evaluating multispecies network persistence. An ecological interaction networks perspective adds additional indicators, including network properties such as connectance, nestedness, modularity, interaction probability, and interaction turnover that are used to predict species interaction networks across space and time (Strydom et al., 2021), as well as interaction strength, interaction rewiring, and spatiotemporal variations in ecological network structure (Quévreux et al., 2024). Lastly, Malishev and Kramer-Schadt (2021) also consider movement and energy budgets, adding potential variables such as dispersal distance, home-range size, migration success, occupancy, colonization probability, and individual energy expenditure that could inform movement-based MFC models. Together, these studies demonstrate that MFC indicators can range from spatial and network-level measures of connectivity, to species-specific movement, population, genetic, energetic, and interaction-based measures.

The new generation of adapted decision-support tools used for incorporating MFC into planning and management includes the Marxan Connect framework (https://marxanconnect.ca), PrioritizR package (https://prioritizr.ne), ZonationR package (https://cran.r-project.org/package=ZonationR), and BlueBioSites (https://gis.sea.ee/bluebiosites) (the latter emphasizing cumulative effects assessment).

Effective and sustainable fish stock management, including the prevention of overfishing, was flagged in expert responses as necessitating MFC-informed collaboration with diverse stakeholders, including international and local fishing organizations. They also recommend identifying key connectivity pathways, such as larval dispersal routes and migratory corridors, and reducing anthropogenic disruptions to these vital connections. The literature supports MPA design establishing clear conceptual connections between connectivity and biological processes such as population dynamics, gene flow, adaptation, and larval dispersal to fishing areas. These links should be aligned with specific spatial planning objectives, including population persistence, genetic diversity preservation, adaptive capacity enhancement, and increased fishery yields. Thus, planners should develop site selection algorithms that prioritize these targets within a comprehensive, multi-objective, and multi-species spatial planning framework to enable more effective conservation efforts (Lagabrielle et al., 2014; Allgayer et al., 2024; Close et al., 2024).

Connectivity metrics used in such processes should be simple, intuitive, theoretically grounded, and empirically measurable to ensure that MFC information is routinely applied in management (Krueck et al., 2022; Beger et al., 2022; Burgess et al., 2014; Smith and Metaxas, 2018). Such metrics revolve around three objectives: (1) maintaining or enhancing self-replenishment of marine species at candidate locations, (2) maintaining or enhancing larval subsidies from candidate locations that rescue or boost productivity at other locations, and (3) providing an insurance policy of external larval subsidies that rescue or boost

productivity at the candidate location. Yet, no universally recognized set of metrics exists because their applicability depends on data availability, technical expertise, computational resources, management objectives, and stakeholder needs (Bode et al., 2016). For long-distance larval dispersal, genetic approaches can estimate MFC by analyzing relationships between population differentiation and geographic distance (Palumbi, 2003; Wright, 1943). Beyond the state-of-the-art metrics derived from biophysical simulations, recent studies have proposed standardized indicators for regular monitoring and for informing Effective Area-Based Conservation Measures (IUCN-WCPA Task Force on OECMs, 2019; Preston et al., 2025). These include connectivity subcategories at both structural and functional levels (Darnaude et al., 2026), supported by methodological frameworks that guide the selection of metrics according to conservation objectives and ecoscape context (Keeley et al., 2021).

Management objectives and decisions that will be informed by these metrics must be considered. Rather than constituting a universally applicable set of metrics, connectivity indicators need to be selected according to the ecological processes of interest, the spatial and temporal scales of management, and the available data and analytical capacity (Keeley et al., 2021; Bode et al., 2016). For example, estimates of species movement and larval dispersal can help identify connections between habitats and inform the location, spacing, and configuration of marine protected areas (MPAs). Network-level metrics, such as the Probability of Connectivity (PC) and Integral Index of Connectivity (IIC), can help evaluate the contribution of individual habitat patches to the connectivity of a wider network. Genetic indicators can provide complementary evidence about population structure and genetic exchange, particularly where direct observations of movement are difficult, but genetic differentiation should not be interpreted as a direct measure of contemporary demographic connectivity (Chen et al., 2024). However, while estimates of self-recruitment and local retention can inform assessments of local population maintenance, additional interpretations may require additional evidence concerning dispersal, recruitment, demographic performance, and the contributions of populations to one another. Different connectivity processes therefore have different implications for management. Where evidence indicates that certain habitats are connected through movement or dispersal, planners may consider protecting those connections alongside the habitats themselves. Where network analyses identify patches that make a substantial contribution to connectivity, these patches may warrant consideration in spatial prioritization, depending on the conservation objectives and on other planning constraints. In situations where evidence suggests that populations depend on recruitment from other locations, management may need to consider ecological connections extending beyond the boundaries of individual protected areas. Nonetheless, in each case, the indicator informs a potential management response rather than independently establishing the appropriate decision or guaranteeing a conservation outcome see (Box. 1).

4.7. Explaining the benefits/risks of addressing MFC to decision makers

Participants addressed the need to justify MFC integration in terms of its tangible added value beyond conservation, and especially the economic, societal, health, and conservation benefits of considering connectivity, as well as showing the risks or different outcomes that may result when connectivity is ignored. There is growing recognition that decision makers benefit from understanding the importance of MFC in conservation planning (e.g., Botsford et al., 2009; Beger et al., 2010). Encouragingly, there have been increased requests for connectivity knowledge during marine spatial planning (e.g. Balbar and Metaxas, 2019; Beger et al., 2022), although the complexity of connectivity data and literature may hinder subsequent application (Darnaude et al., 2026). Thus, to successfully convey the benefits of addressing MFC practitioners are encouraged to explain MFC outcomes in terms of social-economic impacts, and often on a sectoral basis (Garcia Rodrigues et al., 2024).

The costs, risks, and challenges for implementing MFC considerations and measuring their success should ideally be communicated along with constructive recommendations. Challenges may include data uncertainty or gaps, complex implementation methods and high social and/or economic costs (Garcia Rodrigues et al., 2024; Giakoumi et al., 2024). Effectively integrating MFC into decision-making, must balance scientific evidence with practical considerations, and stakeholder engagement playing a crucial role (Giakoumi et al., 2024). Further, decisions are highly context-specific and should be taken on a case-by-case basis (Magris et al., 2016). Risk assessments are valuable tools that are fully integrated into ocean health assessments to quantify, for instance, the vulnerability of systems facing diverse climate impacts (Climate Risk Assessments), or biodiversity impacts for developing strategies and future management scenarios (Biodiversity Risk Assessments). Such multidisciplinary exercises have initially been expanded to evaluate the numerous impacts on connectivity that support many ecosystem processes and services. ‘Connectivity Risk Assessments’ and ‘Integrative Ecosystem Connectivity Assessments’ are tools currently under development to identify risks, benefits and opportunities emerging from the application (or not) of MFC (Liczner et al., 2024). The slow development and uptake of such exercises in marine systems limits our capacity to explain and transfer risks, benefits and opportunities for marine biodiversity conservation (Ghehi et al., 2020; Moland et al., 2025).

4.8. Collaboration of MFC scientists with nature conservation agencies

The study participants recommend that MFC scientists should become more directly involved in marine conservation organizations and networks, including government agencies, NGOs, and multi-stakeholder groups. Existing initiatives for restoration, biodiversity, ocean-literacy, and funding can provide practical opportunities to integrate MFC expertise into conservation activities. MFC research can help predict and anticipate the impacts of climate change which can be applied directly to climate-resilient conservation plans. In addition, the

Box 1
Practical Applications of MFC in Marine Conservation Policy: The Azores Network

The 287,000 km^2 Azores Marine Protected Area Network (RAMPA) illustrates how process-based connectivity indicators can guide management boundaries and protection levels, with 15% of the network fully protected and 15% highly protected. For example, satellite telemetry of migratory megafauna has mapped movement pathways, enabling reserve boundaries to capture dynamic pelagic corridors. Complementing this approach, biophysical models have identified Princess Alice Bank, Dom João de Castro, and Pico Island as key source-sink areas for larval dispersal, supporting their designation as highly protected zones to safeguard larval export. Environmental DNA (eDNA) has provided evidence of biological connectivity between benthic vents and pelagic coral ecosystems, highlighting the importance of integrated benthic-to-surface protection. Together, these examples demonstrate how MFC indicators can translate ecological connectivity evidence into spatial planning decisions, shaping protection zones, reserve boundaries, and restrictions on extractive activities (see Morato et al., 2020).

identification of critical habitats and dispersal corridors can contribute to the prioritization of conservation efforts and mitigation of threats (e.g., Henriksson et al., 2025). Both will benefit from long-term monitoring and sharing data collection frameworks between academics and conservation entities on species abundance, community structure, habitat quality, and environmental factors (e.g., Magurran et al., 2015; Lourenço et al., 2023).

Improving synergies between conservation efforts and MFC scientists, such as through streamlining data gathering and presentation, should be a key goal. One example is identifying the appropriate spatial scale for the implementation of connectivity data in conservation. While connectivity is typically assessed on larger scales, the implementation of conservation actions is often at much smaller scales (Jahnke et al., 2020). Collaborations between agencies and scientists that translate MFC data to inform conservation initiatives are particularly important to make use of the latest state-of-the-art technologies, understand the wider context, and to implement any knowledge efficiently and promptly (Faust et al., 2025; Sturrock et al., in press).

4.9. Monitor and adapt to climate change impact on MFC

The survey answers emphasized that future MFC-informed planning needs to incorporate climate scenarios and adaptive management so that connectivity-informed conservation can anticipate rather than simply react to rapidly changing marine conditions. MFC should be treated as a dynamic property that can change as climate change alters species distributions, life-history traits, phenology, physical ocean conditions, and ecosystem functioning. MFC can be strongly influenced by changing ocean circulation patterns and temperature. However, there is still a profound lack of knowledge on how species will adapt to climate change, and how this will also influence MFC patterns. Increasing temperatures may also create new opportunities for the spread of thermophilic species, while shifting ocean circulation patterns could establish new connections between previously isolated areas (Stachowicz et al., 2002; Matz et al., 2018). There is a need to better characterize biological traits across species and life stages, to improve the parameterization of biophysical and species distribution models (Jahnke and Jonsson, 2022). Such efforts are essential for forecasting future MFC patterns under a range of climate scenarios and enable the development of 'future-proofed' climate-resilient conservation planning (Álvarez-Romero et al., 2018; Coleman et al., 2017; Rieder et al., 2025).

Climate change also alters trophic connectivity patterns, by modifying the cost-benefits of undertaking daily, seasonal or annual migrations to and from established feeding areas. The phenology of migratory taxa has evolved to maximize foraging success, synchronizing migrations with the peak abundance of their resources (Armstrong et al., 2016). Climate change may alter the timings of consumer migrations and resources abundance unevenly, leading to temporal mismatches, where consumer needs no longer align with resource availability (Visser and Gienapp, 2019; Gill et al., 2019). In addition, changes in ocean circulation will relocate areas of high biological productivity and feeding grounds for top predators, such as eddies and front systems (Polovina et al., 2017). Longer trips for top predators feeding in these systems will increase the cost of foraging and could decrease their fitness at the population level (e.g. Antonelis et al., 2003; Thorne et al., 2015).

4.10. Study and reduce the impacts of intensifying blue growth on MFC

Participants addressed expanding activities such as offshore renewable energy, aquaculture, tourism, fisheries, and deep-sea mining as those that will increasingly compete for marine space and may alter connectivity in the next few decades. They argue that MFC should therefore be incorporated into assessments of these activities and into scenario-based planning that evaluates cumulative trade-offs among economic development, ecosystem functioning, and conservation. Indeed, the "Blue Economy" increasingly modifies marine ecosystems, particularly the processes that drive connectivity among populations and habitats (D'Antonio et al., 2025).

Aquaculture and mariculture can strongly affect marine connectivity by facilitating the spread of non-indigenous species and changing dispersal patterns and trajectories. Escapees from aquaculture facilities represent a threat to the genetic integrity and evolutionary trajectory of natural populations (Glover et al., 2017; Bolstad et al., 2021). Intensive aquaculture infrastructures also provide substrate for fouling assemblages and may act as stepping-stones, enhancing both local retention and dispersal of non-indigenous species (Lins and Rocha, 2023). Although regulatory frameworks exist, aquaculture continues to be an important facilitator for species introduction and gene flow between previously disconnected systems.

Maritime traffic creates an extensive, human-mediated network that connects regions far beyond the dispersal capacities of most marine species. Expanding maritime trade will maintain or even further increase human-mediated connectivity in the future (Seebens et al., 2016). Furthermore, busy shipping lanes can alter the migration routes and behaviors of marine mammals due to sound sensitivity and vessel strikes (Erbe et al., 2020).

Fisheries will continue to experience distributional shifts with increased use of marine areas by other sectors leading to fishers being pushed out of traditionally valuable fishing grounds. This displacement can lead to higher fishing pressure on adjacent areas with potential negative impacts on their habitats and species (Bastardie et al., 2025). Climate change presents additional challenges for fisheries and related MFC, with rising temperatures and marine heatwaves affecting the productivity and distributions of commercial fish and shellfish species (Engelhard et al., 2014; Beaudry-Sylvestre et al., 2022; Demirel et al., 2023; Burak et al., 2024). New generation stock assessment models have pushed the operational implementation of spatial considerations, including connectivity, despite inherent inertia in the field (Goethel et al., 2023).

Infrastructure for offshore energy plays a significant yet underexplored role in shaping marine connectivity. Current evidence suggests that these structures facilitate connectivity for various marine species, but the overall impact, whether beneficial or detrimental, remains uncertain and requires further investigation (McLean et al., 2022; D'Antonio et al., 2025).

5. Conclusion and policy implications

The results of the present two-phase survey highlight the need to rethink marine conservation, with MFC providing foundational knowledge to enable effective marine conservation towards the 2030 Agenda for Sustainable Development. We conclude with four policy and management recommendations to help reach marine connectivity and conservation goals.

5.1. Rethinking connectivity

Marine functional connectivity, much like marine conservation, faces different challenges and requires different tools and approaches than those applied in terrestrial systems. New systematic frameworks, with appropriate tools and metrics, need to be identified and applied specifically to marine ecosystems. This should include specialized indicators, technologies, and evidence-based best practices, potentially rethinking the IUCN protected area categories and guidelines that tend to bundle terrestrial and marine conservation areas together. Alignment of emerging MFC indicators with existing global biodiversity indicators and monitoring systems, as suggested in the discussion of indicators above (*Step 6*), could facilitate consistent reporting and cross-scale comparability of connectivity outcomes.

5.2. Redefining conservation objectives and mechanisms

The 2030 conservation goals identified by the Global Biodiversity Framework (CBD, 2022) provide both an opportunity and a risk. This is especially true in the marine environment, where the redefinition of sectoral management policies, such as Other Effective Conservation Measures (OECMs), threatens to undermine conservation goals, contrary to the original motivations for OECMs within terrestrial systems. MFC and conservation experts should therefore develop a working definition of OECMs that emphasizes the connectivity of the marine system and provides clarity for conservation regarding who, what, how, and where. Specifically, who is the competent authority, what are the conservation goals and indicators, how will connectivity be integrated into the process, and where will these areas be designated? These questions must prioritize species and habitats of conservation concern, rather than be a convenient means to fulfil arbitrary national percentage targets. The emerging process and products, such as area-based management guidelines and tool design, must address complexity and conflict, including the need to prioritize and satisfy different interests and interest groups, to ensure the economic, political, and social sustainability of such efforts.

5.3. Creating and applying MFC-informed frameworks at different levels

Conservation efforts should focus on co-developing a validated operational framework for connectivity-informed conservation decisions through a participatory process, involving stakeholders and policymakers on national and international levels. This is because despite the relevance to connectivity and biodiversity conservation, even countries that support conventions promoting MFC integration, such as the CBD, we see the use of genetic indicators being applied inconsistently and unevenly, especially in Ecologically or Biologically Significant Marine Areas (EBSAs) outside the northern hemisphere (Yamakita et al., 2022), suggesting the substantial relevance of local considerations. Thus, while the selection and implementation of specific connectivity metrics should be guided by scientific evidence in conservation efforts at international levels, decisions regarding their adoption and application ultimately rest with national authorities. This is true even for transboundary efforts such as the UNEP Regional Seas program, which already include an inter-governmental collaborative framework based on UN conventions and action plans that advance marine conservation and are connectivity-oriented. Nonetheless, in areas within national jurisdiction, the program can ultimately only advise and support national-level implementation through translating regional agreements into national plans (UNEP, 2026). The involvement of national authorities from the outset is therefore essential to ensure that connectivity-informed conservation approaches are tailored to national contexts, aligned with policy priorities, and feasible to implement and sustain over time.

5.4. Engaging with the future

The triple planetary crisis (climate change, pollution, and biodiversity loss) requires both consideration of MFC from an ecological and biological perspective and a connected view of the world from politicians and decision-makers. Not only are species and habitats connected, but pollution and climate change do not recognize anthropogenic boundaries. This is exacerbated by the connectivity of the marine system and the acceleration of blue growth, as global trade increases and human impacts intensify and move further offshore. MFC researchers already have a broader, more holistic viewpoint than many other scientific disciplines; as such, they should be at the forefront of conversations with other disciplines, stakeholders, and decision makers to co-design strategies for the future management of marine systems. This requires efforts to develop new models and provide comprehensible data to assist decision-makers in taking rational and timely decisions based on robust, science-grounded information, especially in the absence of certainty.

CRediT authorship contribution statement

Yael Teff-Seker: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Peter Mackelworth:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Maria Beger:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Formal analysis. **Anna M. Sturrock:** Writing – review & editing, Writing – original draft, Validation, Formal analysis. **Ewan Hunter:** Writing – review & editing, Writing – original draft, Validation, Formal analysis. **Anna-Maria Addamo:** Writing – review & editing, Validation, Data curation. **Andreu Blanco:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Xiatong Cai:** Writing – original draft, Data curation. **Federica Costantini:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Jochen Depestele:** Writing – review & editing, Data curation. **Nazli Demirel:** Writing – original draft, Investigation. **Simone D'Alessandro:** Writing – original draft, Investigation. **David Goldsborough:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Stefanie Haase:** Writing – review & editing, Writing – original draft, Validation. **Manuel Hidalgo:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Artan Hysa:** Writing – original draft, Validation. **Marlene Jahnke:** Writing – review & editing, Writing – original draft, Validation, Formal analysis. **Zacharoula Kyriazi:** Writing – review & editing, Writing – original draft, Validation, Formal analysis. **Thomas Lamy:** Writing – review & editing, Writing – original draft, Formal analysis. **Filipe Martinho:** Writing – original draft, Investigation. **Susanne Tanner:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis. **Laura Maria Warmuth:** Writing – review & editing, Writing – original draft, Validation, Formal analysis. **Audrey Darnaude:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2026.108423.

Data availability

I have shared my results in the supplamentary materials, only anonymizing my informants.

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