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# Mainstreaming connectivity science in community-based fisheries management

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Functionally connected marine conservation areas are widely recognized as a cornerstone for successful biodiversity conservation outcomes and small-scale fisheries livelihoods. Incorporating fish species movement into fisheries community-based managed areas can catalyse greater conservation and socioeconomic benefits. However, significant gaps exist in aligning small-scale fisheries management with fish connectivity or movement patterns, which can optimize benefits along coral reef systems and associated coastal small-scale fisheries. Here we describe a translational framework that integrates evidence-based connectivity conservation into small-scale fisheries in community-based managed area settings while considering cumulative benefits over time and space to ensure long-term socioeconomic and environmental benefits across such systems.

Connectivity conservation—defined as protecting species' movements and ecological, genetic and environmental associated processes—is increasingly being recognized as an essential management approach but has proved challenging to implement[1,2]. Mounting scientific evidence supports the role of connectivity in maintaining and restoring biodiversity and sustaining ecosystem services that support human and natural well-being[2,3]. Consequently, successive conservation policies, including the Kunming–Montreal Global Biodiversity Framework (GBF), strongly emphasize connectivity conservation[4]. However, a major obstacle to field implementation is the vast disconnect between scientific evidence and management actions on the ground, which inhibits the transition of science and policy into management actions[5,6]. This motivated the establishment in 2016 of a specialist group under the International Union for Conservation of Nature's World Commission on Protected Areas, the Connectivity Conservation Specialist Group, to facilitate "advances in science policy and practice"[7]. With supporting global policy frameworks and the wealth of scientific information available, marine connectivity science is poised for a translational process involving place-based applications and experiential learning with ongoing stakeholder collaboration, particularly in the marine environment[8].

Successful implementation of marine connectivity conservation in area-based management tools (ABMTs) has been documented in established networks of marine protected areas (MPAs) in the Great Barrier Reef, Australia, and along temperate reefs in California, USA[9,10]. In both examples, the MPA networks encompass management zones with different levels of fisheries restrictions, including marine parks, where recreational fishing is permitted, and no-take zones, where fishing activities are not allowed. When no-take zones are strategically placed to protect the movement of marine species populations targeted by fisheries, they result in co-benefits of biodiversity conservation and sustainable fisheries[9,10]. Hence, the growing scientific evidence has led to a consensus that identifying and protecting fish movement patterns, hereafter fish connectivity, can support sustainable fishery yields, can promote the long-term resilience of fish stocks and should be integrated into spatial designs of marine ABMTs[9,11–13].

Despite the potential benefits and major advances in connectivity science, progress towards implementing marine connectivity conservation in ABMTs has been considerably less pronounced, especially in developing tropical countries with high reliance on small-scale fisheries and high poverty levels[8]. In these countries, community-based managed areas (CBMAs) are proliferating as a fisheries management approach, primarily because of challenges with centralized governance approaches and the potential to support small-scale fisheries livelihoods[14]. This approach, also known as fisheries co-management,

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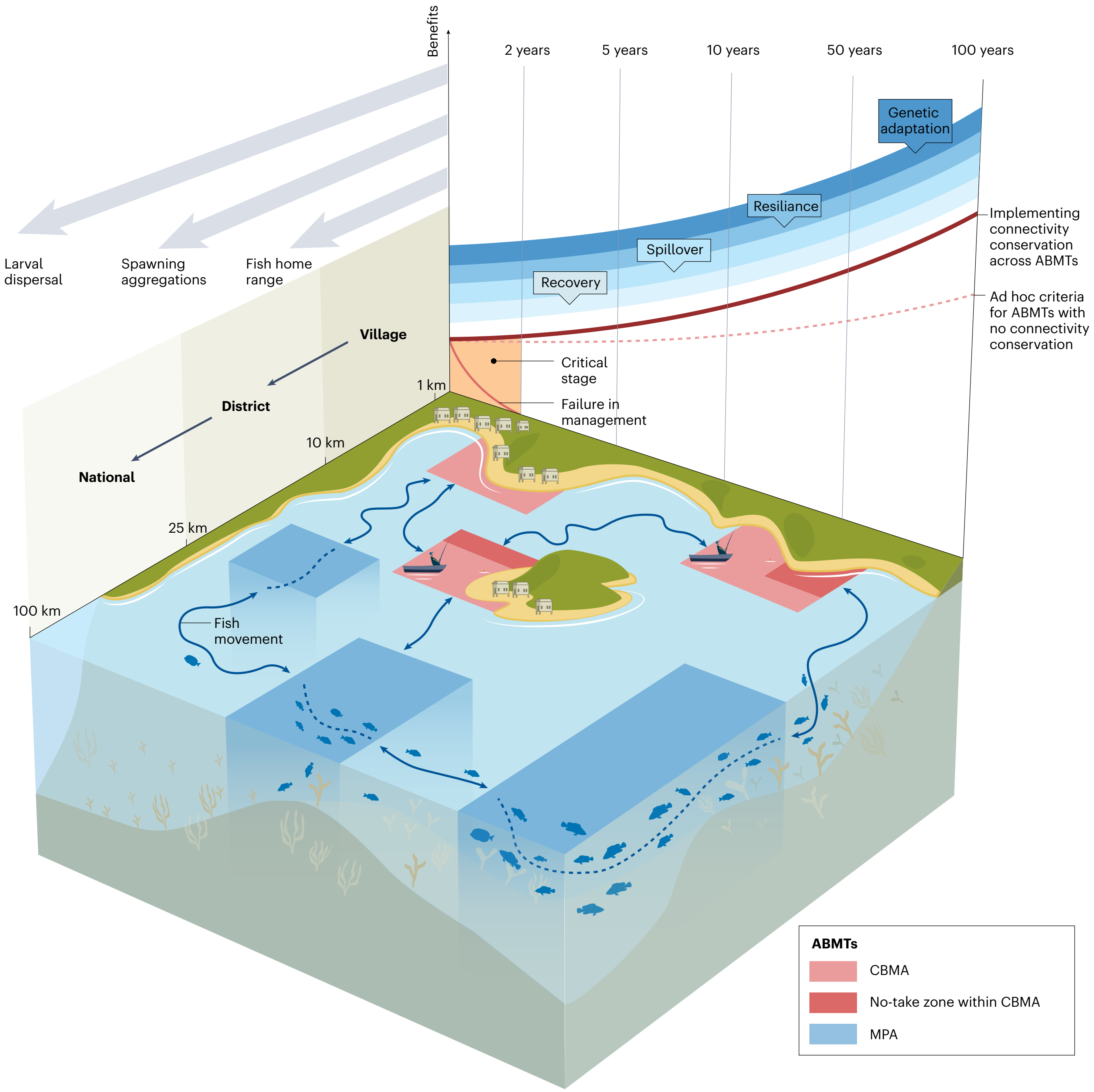

**Fig. 1 | A conceptual diagram of fish connectivity in a small-scale fisheries' socioecological system, illustrating its potential cumulative benefits across different spatiotemporal scales under three distinct fisheries management scenarios.** Fish movement patterns (blue arrows) across different spatial scales[21] (*x* axis) indirectly connect coastal communities with marine areas under different management, creating intricate socioecological networks across tenure and governance levels. Benefits (*z* axis) of ABMTs without incorporating fish connectivity accrue slowly over time (dashed line), while benefits are expected to accrue faster as fish connectivity is harnessed (continuous increasing line), with fish populations' spillover[26], resilience[9] and genetic adaptative capacity[27] among the expected benefits perceived at different spatiotemporal scales (blue colour gradient). Under these two fisheries management scenarios, benefits that accrue rapidly at smaller spatial scales, such as the recovery of coral reef habitats, are expected within the first 2 years from the onset of establishing CBMAs[68]. In a third scenario (continuous decreasing line), ABMT management actions fail to take effect, leading to continued ecosystem retrogression and declining benefits. This can happen if the community lacks the capacity to bear the opportunity costs during the critical establishment stage (light red area), potentially resulting in maladaptive practices such as fishing harder[69]. To ensure the sustainability of ABMTs, particularly of CBMAs and no-take zones within them, support actions are required. These include strengthening tenure and community governance, ensuring costs are not a barrier or burden for under-resourced groups and developing a broader portfolio of livelihoods to reduce fisher vulnerability to market shocks[70].

is a collaborative arrangement between a fishing community and government and/or non-government agencies where both parties share authority and responsibility for managing the fishery[15]. Common tools implemented in fisheries co-management include seasonal closures, no-take zones and gear restrictions[16]. However, these fisheries co-management tools are often ineffective in producing long-term benefits[17], partly because the CBMAs commonly overlook fish movement in their design and application[11,18], undermining their potential for successful outcomes. Translational research aimed at converting connectivity science into practical benefits for small-scale fishery management can address this gap and support the resilience of fisheries-dependent livelihoods in tropical regions[19].

We propose a translational process to mainstream the integration of evidence-based knowledge on fish connectivity with the implementation of CBMAs, aiming to inform conservation efforts and sustainable practices in small-scale fisheries on coral reefs. First, we contextualize fish connectivity as a key ecological process in a socioecological system, illustrating its relevance to fisheries management and accrued fisheries benefits across governance levels and over spatiotemporal scales. Second, we illustrate a conceptual framework for translating connectivity science into practice in CBMA settings and describe how it can be operationalized. Lastly, we explore the current challenges and opportunities for enhancing the long-term effectiveness of nature-based solutions in promoting ecosystem services and strengthening socioecological resilience[20].

## Fish connectivity in socioecological systems

Fish species associated with reef-forming habitats (hereafter, reef fish), despite having a relatively constrained home range compared with their pelagic counterparts, can disperse and migrate up to hundreds of kilometres across a seascape[21]. These movements can occur throughout a fish's life stages and for different reasons, including foraging, reproduction, ontogenetic habitat shifts and dispersal. While several adult fish aggregate for reproduction near their home reef, other large-bodied species can migrate up to 50 km to aggregate for spawning[21]. In the water column, fish eggs and hatched larvae are subjected to regional and local hydrodynamic conditions, which, combined with the pelagic larval duration of the species, play a central role in determining the settlement location of fish larvae[22]. Therefore, different types of fish movement across spatial and temporal scales shape connectivity patterns that maintain the replenishment and resilience of fish populations and thus underpin management actions towards effective, sustainable fisheries[9].

Small-scale coral reef fisheries in developing countries support millions of livelihoods[23]. In these locations, coastal communities can be indirectly connected through fish movement and dispersal[11,12,24]. Identifying connectivity patterns of socioeconomically important reef fishery species across coastal communities' fishing grounds can reveal co-dependencies and co-benefits based on larval supply dynamics and movement patterns of fish populations[12,24]. Importantly, the spatial scale and direction at which fish species disperse and migrate (tens to hundreds of kilometres) may require aligning and coordinating fisheries co-management tools across local, regional and, potentially, international scales[24,25]. Therefore, mapping fish movement across the seascape can reveal the level of cooperation required across multidimensional governance structures to achieve the expected benefits of integrating fish connectivity into marine conservation (Fig. 1). These benefits include reef fish population spillover and resilience and species' capacity to adapt to environmental changes[9,26,27]. Aligning reef fish connectivity across spatial scales with resource-use practices by coastal communities can enhance these benefits, creating an optimal and sustainable multilevel socioecological system for fisheries[24,25,28].

Fisheries' socioecological systems often comprise governance institutions, coastal communities and critical habitats that underpin reef fishery resources[28] (Fig. 2). In these systems, coordinating policy actions can be enhanced by considering scale dependencies between local actions and ecological processes, which are linked to various connectivity conservation benefits. For example, at small spatial scales, a shared vision of ecosystem functioning among households and neighbouring coastal fishing communities can positively impact small-scale fisheries, leading to the successful implementation of fisheries strategies[29,30]. Therefore, the spatial scale at which local fisheries management operates may promote connectivity conservation benefits, such as fish spillover and increased local recruitment of fish species with limited dispersal (Fig. 1). However, conservation benefits that depend on ecological processes encompassing larger spatial scales, such as species spawning aggregations and fish larval dispersal, require strengthening cooperation ties across and between institutions and communities[11,31,32]. This cooperation should align with the movement of fish and their connectivity patterns (Fig. 2).

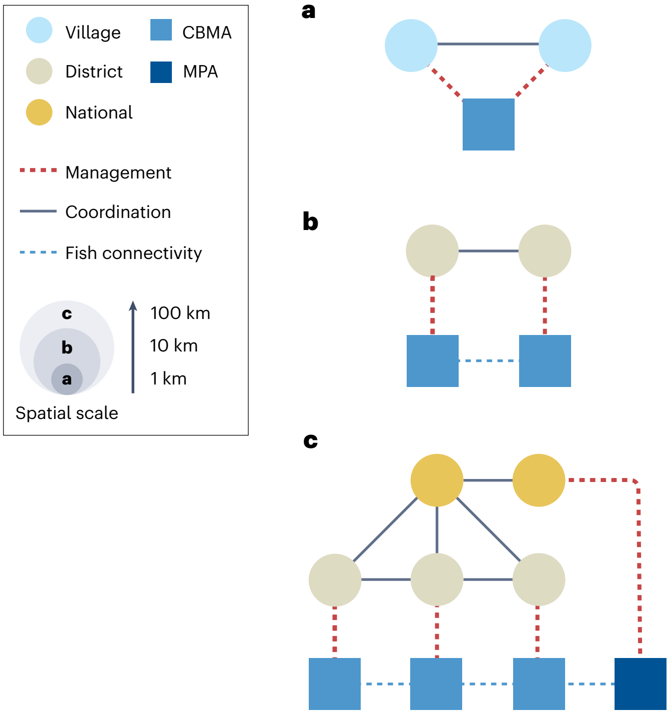

**Fig. 2 | Building blocks representing a socioecological system considering fish connectivity across spatial scales and governance levels. a**, At a small spatial scale, actors represented as villages (coastal communities, light blue nodes) collaborate (grey link) to promote effective fisheries management (dashed red links) in a CBMA (blue square). **b**, When scaling up, actors are represented as districts (beige nodes) where villages are nested. Districts collaborate to manage their respective CBMAs connected through fish connectivity (dotted blue links), promoting socioecological alignment. **c**, At larger spatial scales, mediating actors are represented as national government institutions (yellow nodes) potentially operating at higher administrative levels directly responsible for managing national MPA (dark blue square) or policies that influence fisheries management at small spatial scales. CBMAs and MPAs are connected through fish connectivity (for example, fish spawning aggregations, larval dispersal), representing a network of conservation areas. Coordination and collaboration among actors and mediating actors with different functions in the system are necessary for promoting the alignment of fisheries management strategies with fish connectivity to optimize benefits. Figure adapted with permission from ref. 28, AAAS.

## Integrating connectivity conservation in CBMAs

CBMAs offer an excellent setting for translating marine connectivity science into practice to promote benefits for small-scale fisheries. Their rapid proliferation across the Indo-Pacific and Western Indian Ocean regions as an alternative area-based marine conservation tool has created a more participatory approach to conservation, promoting sustainable community development, equity and social justice[33,34]. However, it is critical to understand the governance context, particularly where and how CBMAs operate and are governed. Since governance is inherently interactive, CBMA contexts are commonly embedded within a hierarchical structure of governments and other institutional arrangements, as well as legislation, policies, and formal and informal regulatory frameworks applied to protect and manage coastal and marine resources. Understanding the hierarchical structures and institutional arrangements can help inform the mainstreaming of connectivity processes into CBMAs to improve the alignment of socioecological networks. Moreover, an active engagement with governance processes should facilitate cooperative and adaptive resource management actions based on the co-dependency of fishing grounds between local communities, which may arise from fish movement patterns (Fig. 3).

The governance of CBMAs is intricately connected to the sharing of fisheries benefits among small-scale fishing communities. Uncovering fish connectivity patterns helps to communicate the co-benefits of fishing grounds as an ecosystem-based adaptation strategy. Such messaging has the potential to inspire cooperative management practices and encourage resource sharing across CBMAs. In the Pacific, small-scale fisheries operating within the Locally Managed Marine Areas network adhere to the '100 percent solution,' a multilevel governance and management framework. This framework allocates and exercises marine tenure rights such as access, management and enforcement in coastal waters. A key objective of this approach is to leverage sustainable small-scale fisheries for increased socioeconomic benefits. Similar frameworks have also been established in other Locally Managed Marine Area networks, including MIHARI in Madagascar and Tengefus in Kenya within the Western Indian Ocean[35,36]. These existing frameworks and networks could serve as conduits for integrating connectivity knowledge into fisheries management decisions while simultaneously promoting biodiversity conservation and the socioeconomic well-being of local communities under different governance and regulatory structures (both centralized and decentralized).

## From theory to practice

The operational framework for implementing connectivity conservation in CBMAs is presented in Fig. 4. Its operationalization will typically involve a collaborative effort among various stakeholders. This bottom-up framework is underpinned by co-creation and the integration of scientific and traditional knowledge. It builds on existing other effective area-based conservation measures (OECM) and CBMA frameworks[15,37] and extends them to explicitly identify fish movement as a cornerstone ecological process to be harnessed for sustainable small-scale fisheries. The framework comprises six steps: (1) assessing the local context, (2) engaging with stakeholders and building key partnerships, (3) mapping socioecological networks underpinned by fish connectivity, (4) aligning fisheries management tools with socioecological networks, (5) implementation, and (6) monitoring benefits. Importantly, the framework recognizes that while this path has been traversed before, the challenges that persist in undermining the on-the-ground implementation have endured.

### Evaluate local context

This initial step is crucial for gathering the necessary information to inform a theory of change relevant to the specific circumstances of the social and ecological systems in the region of interest. Here situation analysis is conducted to evaluate the social, ecological, economic and political contexts, which can differ across different communities. Moreover, relevant contextual factors, such as the existing fisheries management practices, local customs, proximity to markets and the community's reliance on fishing, are assessed. These assessments provide a basis for implementing connectivity conservation within the existing fisheries' management structure.

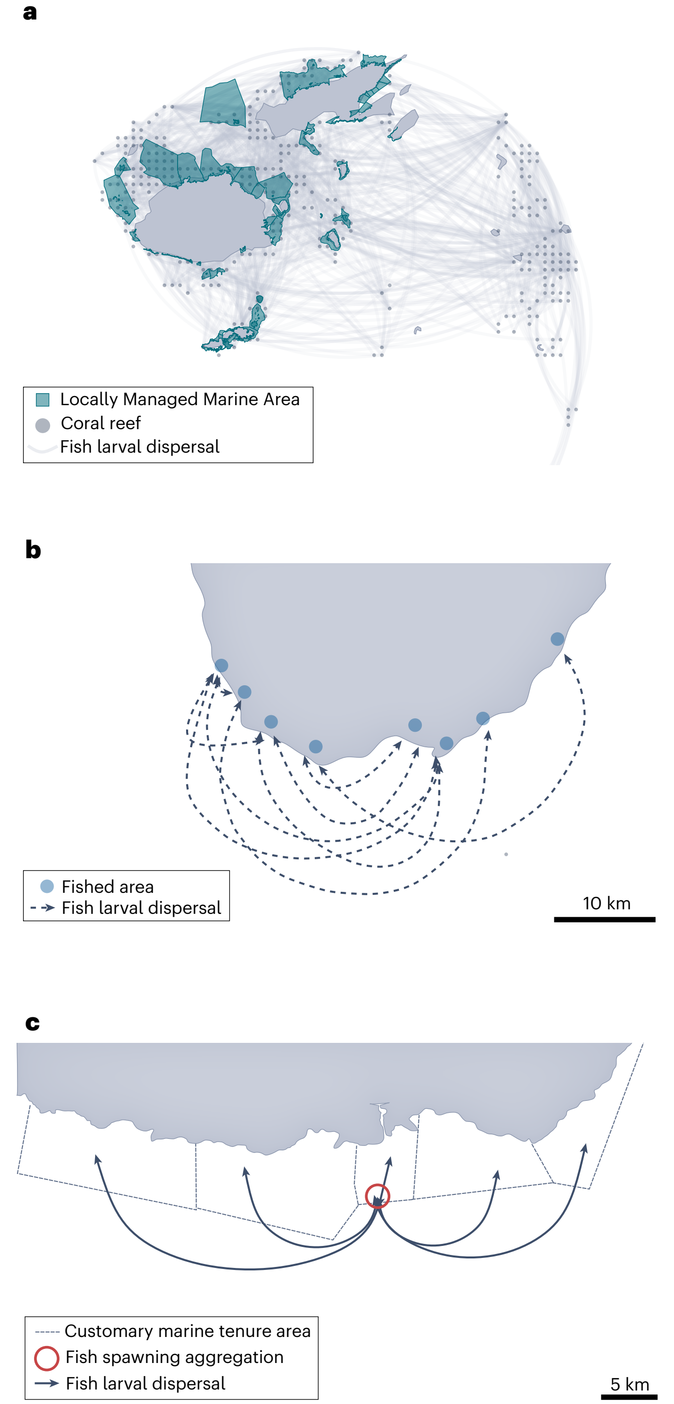

**Fig. 3 | Fish movement among coral reefs across different spatial scales connects coastal communities and CBMAs. a**, Larval dispersal simulations using biophysical models demonstrate probabilities of reef fish connectivity among CBMAs in Fiji. **b**, Reef fish populations from fished areas are connected through fish larval dispersal and indirectly connect coastal communities in the Philippines. **c**, Co-dependencies among customary marine tenure areas were uncovered by genetic analyses of fish cohorts and adults from a single coral–trout spawning aggregation event in Papua New Guinea. Panels adapted with permission from: **a**, ref. 3, AAAS; **b**, ref. 24, Springer Nature Ltd; **c**, ref. 12, Elsevier.

### Engage and analyse

This step aims to identify and characterize fisheries stakeholders that are directly and indirectly affected and influencing policy decisions and management in the region. Stakeholders include local communities, government agencies, and individuals or groups outside the system boundaries but with shared interests. Local communities are directly involved in small-scale fisheries, making it crucial to understand their roles, responsibilities, and the customs or laws governing

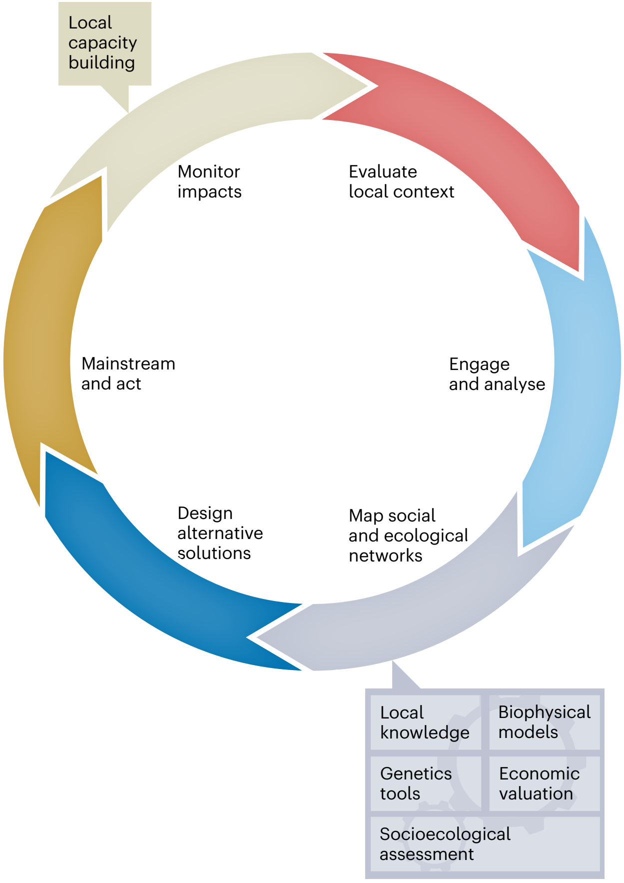

**Fig. 4 | Operationalizing connectivity process within CBMAs summarized in six steps.** This bottom-up framework aims to achieve sustainable development of small-scale fisheries by integrating evidence-based connectivity conservation into CBMA settings.

their interactions. These communities play a central role in enabling behavioural changes and sustaining benefits over time. Government agencies can provide the necessary resources for positive change, such as enforcement and financial support. They create enabling legislation, oversee fisheries management and offer aid to support sustainable practices. Communities located beyond the region of interest but interested in the project outcomes can also represent critical external stakeholders. Once stakeholders are identified, partnerships can be established, followed by various activities to build their capacity and trust. With partnerships in place, the governance system related to small-scale fisheries is also analysed. This involves identifying gaps in existing practices and regulations and recognizing institutions' legal frameworks, rights, ownership and management mandates for fisheries.

### Map social and ecological networks

This step involves mapping ecological and social connections among coral reefs, local communities and institutions operating at higher administrative levels using a range of available tools to understand the state of socioecological alignment in the region. The combination of different tools (illustrated as engines in Fig. 4), such as cutting-edge genetics and biophysical modelling, is increasingly used to reveal connectivity and demographic patterns of marine species across spatial scales. Using genetic methods, such as parentage analyses and isolation by distance, it is possible to determine marine species' population relations and structure at scales relevant to small-scale fisheries[22,38]. The growing level of understanding of fish larval behaviour and reproductive traits[39,40] has improved the accuracy of high-resolution ocean numerical models for simulating fish connectivity across different spatial scales[22]. Likewise, scientific information on species' home range, habitat use and advances in acoustic telemetry techniques have supported mapping fish connectivity patterns relevant to a range of existing management tools[21,41]. Using participatory mapping methodologies[42], traditional ecological knowledge can provide critical details on the species of interest at smaller spatial scales, such as habitat use, spawning time and location, fishing effort, and temporal perception of catches[43,44]. Similarly, traditional ecological knowledge can inform the mapping of benthic habitats that are important for fish recruitment and can be used to refine outputs of biophysical modelling (for example, benthic layers). Field assessments of social, economic, cultural and political factors can uncover the degree and presence/absence of cooperation ties between local communities and institutions[25,29]. Underwater surveys provide critical information on reef habitat conditions and fish assemblage structure and their response to different management practices[17,45]. These social and ecological data are then used to identify and map the socioecological networks shaped by fish connectivity and social, economic and institutional relationships. Subsequently, the strength of the alignment between the social and ecological network is analysed[25,28].

### Design alternative solutions

Through a place-based participatory research action, this step aims to generate a set of alternative optimal fisheries management actions within the existing socioecological system that can build resilience of ecosystem services and represent a desired future. To achieve this, understanding the present-day socioecological network and its associated causal inferences is necessary. This understanding may be achieved through counterfactual thinking, which involves projecting scenarios with/without intervention[46] and backcasting, among other methods for exploring policy interventions and trade-offs. In this step, it is important to carefully consider the spatiotemporal scales at which different fish connectivity processes might occur to communicate their expected benefits within an ecologically realistic time frame. This is particularly important because the benefits of protecting the connectivity of fishery species may take years to become evident (for example, spillover and stock resilience[9,26,47]). As part of this action research, fish population dynamics and connectivity modelling can be integrated to evaluate fish stocks' responses to fishing management actions and climate change over time[48–50]. Fisheries management actions, however, represent just one factor influencing observed management impacts. Environmental, economic and social controls play a crucial role in shaping socioecological outcomes and should be considered when exploring alternative interventions. Moreover, focus group discussions and interviews with key informants can help determine stakeholders' awareness, knowledge, acceptance and compliance regarding marine conservation and fisheries management to develop more realistic management strategies and outcomes scenarios. This integration can offer valuable insights into the potential effects of the alternative solutions, allowing policymakers to make more informed decisions regarding the sustainable management of fish stocks within socioecological networks.

### Mainstream and act

In this step, community and government agencies are presented with the identified optimal scenarios of area-based fisheries management for decision-making. Importantly, the potential limitations and uncertainties in methods and data gaps should be acknowledged to build confidence and trust among stakeholders[51]. At this stage, support actions are required, such as strengthening tenure and community governance, developing a broader portfolio of livelihoods to reduce fisher vulnerability to market shocks, and strengthening management capacity, including the development of management plans and financing to offset possible opportunity costs associated with management actions.

### Monitor impacts

Effective conservation efforts require ongoing monitoring to assess their impact[52]. In the CBMA context, social (for example, gender equality), economic (for example, income) or environmental (for example, biodiversity) impacts resulting from implemented changes need careful evaluation[37,53]. While CBMA benefits can be difficult to perceive and measure in economic terms[54], existing methods can be adapted and applied within the context of the mapped socioecological network. For example, the evaluation of economic revenue from local catches according to fisheries management strategies[55,56], changes in recruitment and density of target species according to spawning aggregation protection status[31], and communities' overall well-being[57]. Stakeholders should collaborate to co-develop effective evaluation tools for measuring the impact of conservation efforts on the socioecological systems while also ensuring local capacity building and autonomy for monitoring programmes. By combining traditional knowledge with existing methods, stakeholders can enhance their collaborations and work together to create effective ways of evaluating the impact of conservation efforts on connectivity, which is currently considered a research gap. Therefore, monitoring the benefits and impacts of connectivity conservation in CBMAs is key for addressing current research gaps and reviewing spatial management plans, which may be of local and national interest[11].

## Opportunities and challenges

CBMAs are essential in global conservation policy, enhancing the sustainability and well-being of both nature and people through sustainable fisheries management practices[58]. The GBF recognizes that stewardship by local communities is critical to global efforts to conserve biodiversity, particularly in the expansion of OECMs envisaged under Target 3[59]. However, for CBMAs aimed at promoting sustainable fisheries to be recognized as OECMs, fisheries management strategies adopted by coastal communities must balance long-term biodiversity conservation with the sustainable use of marine resources[53,60]. The transition from CBMAs to OECMs can be accelerated by mainstreaming connectivity science in their establishment and operation, along with other biodiversity and ecological considerations. The mainstreaming should be supported through a participatory process and consultation with communities, where local socioeconomic and cultural contexts and traditional knowledge are considered. This approach aligns with the criteria for identifying and evaluating OECMs, including positive long-term biodiversity and ecosystem services outcomes[37], while also empowering local communities, as envisaged by the GBF's Target 22.

Implementing connectivity conservation within CBMAs requires strengthening financing mechanisms and coordination among institutions. This is critical for incentivizing conservation actions and addressing current challenges in participatory action research, including technology and capacity. Addressing opportunity costs is critical in determining the CBMA progression or regression trajectory. Various strategies for managing opportunity costs exist, and successful examples can be found in other sectors, such as agriculture and forest management. These sectors have effectively applied payment-for-ecosystem-services strategies for communities or individual groups[61]. For example, identifying connectivity patterns in the socioecological space can inform payment for ecosystem services in small-scale fisheries and other compensation mechanisms based on opportunity costs for the loss of fishing ground. For example, one community might protect a reef that exports fish larvae, thereby promoting fishery benefits or recovery in connected reefs acting as fish larval sinks[62,63]. These fish population dynamics can be revealed in step four of our framework (Fig. 4), where mapping socioecological networks may reveal such dependencies and inform decisions on the relative investments needed to implement the identified alternative plans.

Challenges of mapping fish movement through spatiotemporal scales, including tracking fish larval and adult movement, have fuelled research and significant advancements in methods for understanding the processes underpinning fish connectivity in both oceanography and fish ecology disciplines[22]. However, the costs associated with cutting-edge methods are prohibitive, particularly for developing countries, limiting the accuracy of connectivity models and replication across scales and species. Similarly, highly resolved hydrodynamics and biophysical models for simulating detailed larval dispersal patterns[64] can take substantial effort to develop and are lacking in most developing countries. Therefore, enabling developing countries to access necessary technology and data analytics is a priority to overcome obstacles in implementing connectivity conservation. This is essential for achieving successful biodiversity and socioeconomic goals, as outlined in OECM and CBMA guidelines[15,37].

Funding for conservation actions relative to the desired impact represents a major shortfall. Although one might expect higher funding for less-developed countries with high biodiversity, significant inequities in funding allocation exist. When controlling for land area, governance and inequality, countries with low biodiversity received more funding per capita than those with high biodiversity[65]. Therefore, strategic channelling of conservation funds is necessary to achieve impact on the ground. It is common to find several projects by different institutions working concurrently on similar problems, which can lead to duplication of efforts and, overall, less-effective outcomes. Given the fragmented nature of the funding landscape, better coordination among institutions can help leverage limited resources to achieve impact. Likewise, a programmatic approach that prioritizes empowering and building the capacity of local stakeholders on the project's design, data collection and impact monitoring is required to ensure sustainable outcomes and long-term impacts[66]. Thus, there is a need and an opportunity to form partnerships for connectivity conservation in small-scale fisheries, where relevant projects can be coordinated under a common goal of operationalizing connectivity conservation in action research, with shared values, effective communication and a commitment to long-term sustainability. Government funding agencies, private philanthropies, businesses, venture capital providers and non-governmental organizations are in a privileged position to influence conservation actions and foster a more equitable and inclusive future. They can achieve this through several grant practices that prioritize collaboration, action research and translational science, and incorporate project deliverables that incentivize co-designed and co-produced research projects[67].

Existing global policy instruments increasingly recognize the critical role of CBMAs in sustaining marine conservation efforts and securing social, ecological and economic benefits for the future. This global effort also pushes for increasing the effectiveness of CBMAs and optimizing their designs to co-benefit biodiversity and communities. The proposed framework in this Perspective is compatible with the existing OECM and CBMA guidelines. However, it also synthesizes and harnesses the potential of connectivity conservation to expedite and further expand marine conservation areas in more meaningful ways. If the framework is to be implemented, CBMAs can contribute to greater conservation outcomes, including biodiversity persistence and increased social, economic and ecological resilience of communities.

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## Author contributions

L.F., J.M., A.T., B.S., V.H. and A.S. conceptualized the paper. L.F. and J.M. wrote and revised the first draft and created conceptual frameworks. L.F. designed and edited the figures.

## Competing interests

The authors declare no competing interests.

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