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Coral reefs span borders, so must solutions: transboundary conservation in complex political environments

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Coral reefs face escalating threats from climate change, yet reducing greenhouse gas emissions alone will not ensure their survival. Local and regional conservation efforts are urgently needed to address immediate, human-induced stressors and build resilience. Although conservation often begins locally, the interconnected nature of reef systems that span borders demands transboundary management, international coordination, and robust governance frameworks. In 2024, a multidisciplinary group of coral reef scientists and conservationists convened at Stony Brook University to develop strategies for strengthening reef resilience globally and regionally, with an emphasis on the Red Sea and Caribbean reefs. Using participatory systems mapping, the group produced a framework identifying six priority areas for international and transboundary action: conservation finance; global knowledge management; regional political coordination; area-based management; ecosystem restoration; and strengthening stakeholder capacity and engagement. The findings demonstrate commonalities as well as regional nuances for coral conservation, and the approach can be replicated elsewhere.

Coral reef ecosystems are among the most biologically diverse and economically important marine habitats. They support an estimated 25% of all marine species and provide hundreds of billions of dollars annually in goods and services, including coastal protection, fisheries, tourism, and medicine, among other benefits[1–5]. However, coral reefs and the ecosystem services they provide are being lost at an alarming rate. Since the mid-20th century, degradation has been driven by localized threats such as pollution and overexploitation, but global warming from climate change is now the greatest threat[6,7]. More than half the world's coral reefs have been lost since the 1950s, and 70–90% of what remains is projected to be lost this century even if international measures keep warming below 2 °C[8,9]. Coral reefs—as we know them—may be the first ecosystem to be eliminated from Earth in the Anthropocene, and this is likely to occur within some of our lifetimes.

Furthermore, the years 2023–2024 saw the fourth and most extensive global mass bleaching event in recorded history[10,11], with 2024 being the hottest year on record and the first to exceed 1.5 °C above pre-industrial average global temperatures[12,13]. The 2024 bleaching event drew special attention to coral reefs, including a Special Emergency Session for coral reefs at CBD COP 16 in Cali, Colombia, in 2024[14]. Given the record bleaching in 2023–2024, projected future warming, and ongoing reef degradation, scientists and conservationists must consider the complexities of coral reef protection and identify specific, actionable pathways that can be pursued with the support currently available. This process is crucial to garner the necessary political and financial backing to protect remaining reefs and prioritize those that have been shown to be more resilient.

To protect coral reefs, it is essential to both recognize and communicate that there is reason for *hope*. There are several examples of reefs around the world that have shown remarkable resilience in the face of stress, with high tolerance to warming or acidifying conditions due to a range of factors, including inherent genetic resilience, adaptation, and unique geological or

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environmental factors (Table 1). And through dedicated research, the scientific community is gaining a better understanding of the mechanisms behind this resilience. These insights offer the potential to enhance resilience at larger scales.

Climate change is the greatest threat to coral reef health, and reducing greenhouse gas emissions remains the most essential strategy for ensuring long-term survival. At the same time, minimizing additional local and regional threats and pressures is critical for supporting reefs that show potential resilience to climate-driven impacts, particularly ocean warming[15–17]. Examples of addressable site- or regional-level threats include managing wastewater pollution, sedimentation and other forms of land-based pollution, coastal development, destructive tourism, destructive fishing such as dynamite fishing, and overfishing of key species that maintain reef stability, such as apex predators and grazers. In parallel, coral restoration might help to rebuild damaged reefs and enhance reef resilience[13,18,19]. Ultimately, securing a sustainable future for coral reefs requires effective local management to support resilience alongside global efforts to mitigate greenhouse gas emissions.

Resilience broadly refers to the capacity of a system to maintain key functions and processes in the face of pressures by resisting, recovering, and adapting to change[20,21]. Here, we define coral reef resilience to climate change as the capacity of corals and associated species to tolerate warming and acidification while maintaining survival, reproductive viability, and overall health of the ecosystem. To foster resilience for coral reefs, coral reef managers should widen their focus beyond ecological processes to also include the interconnected resilience of coastal human communities. Social resilience includes the capacity of local communities to respond and adapt to change, as well as the capacity of governing structures to support the resilience of the socio-ecological reef system through changing social and environmental contexts[22].

Management for coral reef resilience, therefore, requires prioritizing actions across social, ecological, and governance dimensions. Some of these actions are globally applicable and may include implementing area-based conservation such as marine protected areas (MPAs), protecting a diversity and redundancy of species, habitats, and functional groups, supporting research into innovative strategies to support resilience, and building adaptive management in governance systems[23]. However, while many coral reef resilience-based management strategies have commonalities across the globe, varied states of coral reef health, distinct governance, and ecological and socioeconomic contexts call for actions that are tailored to specific local and regional contexts.

Tailoring management to local and regional contexts also means considering the ecological realities of coral reefs themselves—intricate, interconnected systems that transcend political boundaries and depend on surrounding ecosystems for their resilience. Tiny individual coral polyps together form collective coral skeletons, which aggregate with other coral skeletons to form large reef structures that span across international boundaries, sometimes for thousands of square kilometers. Coral reefs require healthy ecosystems around them, with biodiversity within reefs, with strong ecosystem connectivity having shown greater resistance to human pressures in several regions around the world[24]. Connectivity is also projected to influence the potential for reefs to recover from harmful events[25].

Connectivity is crucial to reef health and climate change resilience for several reasons. First, reef health and resilience rely on the dispersal of coral larvae from surrounding reefs, carried by ocean currents for up to hundreds of kilometers, to support genetic exchange that can promote resilience through higher overall genetic diversity as well as the exchange of specific genes that may promote resilience[26,27]. Reef connectivity is also vital for exchange and population health of other taxa crucial to ecosystem stability, such as grazing and predatory fish[24,28]. Connectivity with other tropical ecosystems, such as healthy mangroves and seagrass beds that act as nursery grounds, providing habitat for early life stages of invertebrates and coral reef fish, can also influence reef health[29]. Surrounding marine and terrestrial ecosystems are also important for regulating nutrient and sediment input that affect water quality, and factors such as deforestation or unsustainable land use have been historic drivers of degradation in regions like the Caribbean[30].

Considering the importance of connectivity across reefs and other ecosystems, and the fact that many reef systems span several countries (e.g., Coral Triangle), coral reefs require multinational approaches for transboundary, seascape and landscape scale conservation.

To date, many global and regional policy frameworks and multinational initiatives could potentially galvanize international cooperation for coral reef conservation and resilience via control of greenhouse gas emissions and other threats to reef health. The United Nations Framework Convention on Climate Change (UNFCCC) is the chief forum for global climate change mitigation. The Paris Agreement, formalized in 2015 by the 196 countries party to the UNFCCC, is the main body of United Nations (UN) legislation that sets goals for reducing greenhouse gas emissions and mitigating warming to limit global temperature below 1.5 °C above pre-industrial levels[31]. Other relevant international frameworks are specific to global socioeconomic development, such as the UN Sustainable Development Goals (SDGs) that include the ocean-specific SDG 14 with relevant

Table 1 | Demonstrated examples of potential climate change resilient reefs

Location	Description
Rock Islands, Palau	Woods Hole Oceanographic Institute's "Super Reefs" program has identified potential resilient reefs in four countries in the tropical Pacific[161]. One example is the Rock Islands in Palau where a 2015 study found that corals in Palau's naturally low-pH reefs have adapted to acidic conditions, maintaining calcification rates similar to those in higher-pH environments, suggesting potential resilience to future ocean acidification scenarios[162]. Another 2022 study found that corals in the same archipelago also demonstrated remarkable heat tolerance[163].
Great Barrier Reef, Australia	The Great Barrier Reef has made news from suffering multiple mass bleaching events in the last decade[164]. However, recovery within the reef has varied significantly at local levels. Research has identified local areas of unique heat tolerance potentially linked to genetic adaptations[165].
Kenya-Tanzania Transboundary Conservation Area (TBCA)	In the Pemba Channel within the Kenya-Tanzania Transboundary Conservation Area, deep-water channels and proximity to open ocean currents have helped regulate water temperatures over some coral reefs during marine heatwaves. These reefs have escaped bleaching suffered by surrounding reefs without these cooler waters and could be an important climate change refuge[166].
Gulf of Aqaba, the Red Sea	A series of studies found that corals in the Gulf of Aqaba (GoA), a northeastern extension of the Red Sea, exhibit remarkable resistance to rising water temperatures, surpassing the resilience of many corals in other regions worldwide[68–73]. During the 2024 global mass bleaching event, only a small handful of species experienced bleaching despite prolonged exposure to temperatures as high as 31.9 °C (30 Degree Heating Weeks)[11,80–82].
Kāne'ohe Bay, Hawai'i, USA	Reefs in Kāne'ohe Bay suffered decades of effects from rampant sewage pollution from the 1930s–1970s, yet recovered within 20 years after sewage input was diverted. They have since shown higher resilience to warming and acidification compared to surrounding reefs, including during some bleaching events in the last 20 years, and their inherent resilience has been linked to having lived under stressful conditions in years past[167,168].

targets such as SDG 14.5, to protect 10% of the ocean by 2020[32]. Parts of the UN SDGs overlap with the Convention on Biological Diversity (CBD)'s 2022 Global Biodiversity Framework (GBF), in which member countries agreed to several targets to halt biodiversity loss by 2030 and reverse declines by mid-century, including a target to protect 30% of land and sea by 2030 (Target 3)[33].

There are also several international platforms or programs specific to coral reefs, such as the Global Fund for Coral Reefs[34], International Coral Reef Initiative (ICRI)[35], and the Coral Reef Breakthrough[36]. These programs can help mobilize funding, build global awareness, advocate for coral reef conservation, or establish national-level programs. At the regional level, efforts such as the Coral Triangle Initiative in the Indo-Pacific, the Regional Organization for the conservation of the Environment of the Red Sea and Gulf of Aden, the Mesoamerican Reef Fund (MAR Fund), and the Kenya-Tanzania Marine Transboundary Conservation Area, provide frameworks for coordinated action tailored to specific ecosystems and governance contexts.

Despite global and regional initiatives, in 2024 global temperatures exceeded the Paris Agreement's temperature threshold of 1.5 °C above pre-industrial levels for the first time. The SDGs remain largely unmet despite their approaching 2030 deadlines, and none of the CBD Aichi Targets (the predecessor to the GBF) were fully achieved[37]. As coral reefs continue to decline, effective international governance to support reef resilience and conservation is critical. With many 2030 targets looming, and conversations beginning on post-2030 agendas[38], 2025 is a timely moment to review opportunities to enhance international governance and transboundary coordination for these ecosystems.

These challenges underscore the urgent need for innovative, coordinated, and actionable strategies to strengthen international governance and political cooperation for coral reef resilience. Against this backdrop, an NSF-funded research program investigating coral reproduction and resilience in the Gulf of Aqaba convened an international workshop at Stony Brook University in New York, USA, in June 2024, titled, "Blueprints for Resilience: A workshop on coral reef resilience, conservation, and charting a roadmap for scaling effective conservation interventions for climate-resilient reefs." The initiative aimed to harness the collective expertise of a multidisciplinary cohort of global experts in coral reef science and conservation to forge pathways to support climate change resilience and the conservation of coral reefs worldwide through international coordination and transboundary management. The workshop brought together 20 scientists, conservation practitioners, and other experts from 12 institutions and six countries, representing universities, NGOs, and governance institutions. Participants included coral physiologists, reef ecologists, marine conservation policy experts, conservation social scientists, ocean finance experts and practitioners, and field-based conservation program managers. Using participatory systems mapping[39–41] (see Methods), workshop participants charted road maps for effective conservation and building resilience of coral reefs at the global level and at the seascape level for two different coral reef regions: the Red Sea and the Caribbean. This paper presents the results from the workshop with recommendations for advancing the findings for transboundary coral reef conservation and resilience around the world.

Results

Participants of the 2024 workshop were divided into three breakout groups: Action at the Global Level, Case Study #1: The Red Sea, and Case Study #2: The Caribbean. The following subsections represent the outcomes for each group. The systems maps figures are based on initial systems maps developed during the workshop (see methods), and the text reflects the discussions and takeaways. Leaders from each breakout group were responsible for drafting the results write-up for their respective sections.

Action at the global level

Global policy frameworks for biodiversity conservation can support on-site efforts for coral conservation. In return, local action is required for fulfillment of some global targets, such as GBF Target 3 to protect at least 30% of marine and coastal areas (30 by 30) and Target 2 to restore at least 30% of degraded marine and coastal areas[33]. The International Coral Reef Society (ICRS) also calls for mitigation of local threats to improve reef condition and for investment in coral reef restoration alongside global climate action[42].

Local management strategies require tailoring management plans to specific reef conditions and threats to ensure targeted and effective conservation efforts. But there is the potential for action at the local level to benefit from targets, standards, or other guidance at the global level, such as best practices for marine protected areas[43]. Below, we outline some priority areas for action by the global community that can help build resilience at various levels of coral reef governance and management, including: (i) global climate change mitigation, (ii) area-based conservation, (iii) community engagement, and (iv) research and innovation.

First, for global climate change mitigation, there are many international agreements and initiatives that can serve as important vehicles to reduce greenhouse gas emissions, the primary driver of coral reef degradation. The UNFCCC has served as the foundation for multiple global commitments, such as the Kyoto protocol adopted in 1997 that went into effect in 2005 and introduced emission reduction commitments for developed countries[44]. Later, the countries party to the UNFCCC adopted the Paris Agreement in 2015, which came into force in 2016[31,44]. However, there is growing evidence that current mitigation efforts, as well as future emissions commitments, are not sufficient to achieve the temperature goals set by the Paris Agreement[13,45,46]. Based on these factors, and building on the workshop's outcomes, there is an urgent need to explore further measures to strengthen international agreements, implement carbon pricing and regulations, expand renewable energy, support climate adaptation and resilience, and strengthen protections for carbon-sequestering ecosystems like rainforests and mangroves.

Second, on area-based conservation, effective Marine Protected Areas (MPAs) can mitigate threats like overfishing, habitat destruction, pollution, and other threats that can undermine coral reef resilience[43,47,48,49,50]. MPA networks can facilitate the movement of coral larvae between reefs, which can promote genetic diversity and introduce traits that enhance resilience. For example, larvae from thermally tolerant populations could seed vulnerable reefs, potentially spreading adaptive traits. Other effective area-based conservation measures play a complementary role to MPAs in coral reef conservation. For example, other effective area-based conservation measures (OECMs) are areas that achieve effective conservation of biodiversity without being formally designated as protected areas[51]. These areas have the potential to contribute to coral reef resilience, biodiversity, and ecosystem service protection through sustainable practices or traditional stewardship.

Global key actions to enhance area-based conservation efforts' ability to build climate resilience include expanding and strengthening MPAs and OECMs by prioritizing climate-resilient sites and improving enforcement mechanisms using technology (i.e., satellite monitoring, AI-assisted tracking), strengthening global and regional MPA governance, improving financing and incentives for conservation and enhancing monitoring, compliance, and adaptive management. Global policies to strengthen MPAs, such as UN Sustainable Development Goal 14.5 and the CBD Aichi Targets 3 and 11 mentioned above, will continue to be essential for advancing reef conservation efforts globally. However, the global community should consider that some critical ecosystems, such as surviving, resilient coral reefs, may merit more than 10% or even 30% protection.

Third, for community engagement, global policy frameworks should help empower local communities to implement sustainable practices and participate in and lead conservation efforts. Global initiatives to support community engagement in coral reef conservation can include education and awareness campaigns, incentivizing sustainable practices, strengthening policy and legislation, supporting community-led conservation and incorporating science and traditional knowledge[52]. Bringing together these different knowledge streams across Indigenous, Local, and more

mainstream knowledge such as from the global science community to support conservation planning, including planning that is led or co-developed with Indigenous Peoples and Local Communities, can improve effectiveness, foster equity, and ensure long-term community buy-in and stewardship[52–54].

Collaboration across sectors (governments, NGOs, scientists, and the private sector) is also critical and successful partnerships should incorporate different stakeholders, such as local governments, Indigenous Peoples and Local Communities, and fisheries, tourism, or other commercial activities, to take shared responsibility for reef conservation. International policies can ensure the integration of coral reef education into curricula and promote sustainable coastal management at all levels of government.

One example of how community engagement at a global scale can support coral conservation is the International Year of the Reef (IYOR)[55]. Initiated by ICRI in 1997, and held again in 2008 and 2018, IYOR stimulated a series of regional activities that—in 2018—engaged 60 organizations across 61 countries, often supported by funding from ICRI partners that brought together communities, organizations, governments, and the private sector to focus on coral reef conservation globally. Communities were encouraged to take part in coral reef monitoring, restoration projects, beach cleanups, and awareness campaigns. This initiative facilitated broad collaboration between local communities, scientists, environmental NGOs, and governmental bodies, and is an example of how global platforms for community engagement can help to strengthen local conservation efforts, raise awareness, and showcase the power of collective action in supporting coral reef protection.

Fourth, research and innovation is a key area of focus for advancing measures such as coral reef restoration techniques. When planned appropriately, coral reef restoration can potentially play a supportive role in building resilience for coral reef ecosystems[52]. Coral reef restoration broadly refers to a suite of interventions aimed at improving reef structure and ecosystem function and increasing the populations of key reef species[56]. Some examples of global restoration efforts to combat coral reef degradation include those applied by the Coral Triangle Initiative (CTI), the Great Barrier Reef's Coral Reef Restoration and Adaptation Program, The Ocean Agency´s "Mission 2020", restoration of *Acropora* corals in the Caribbean, and the Bahamas Coral Restoration Initiative. Several World Heritage coral reefs are undergoing restoration, with a specific focus on enhancing their resilience to climate change through coral gardening and restoration programs[57].

Coral gardening is a two-phase restoration method where small coral fragments are grown in nurseries and later transplanted onto degraded reefs to restore coral cover[19,56]. It is the most widely used intervention, but other common interventions include larval-based restoration, reef substrate enhancement (e.g., artificial reefs), reef substrate manipulation (e.g., rubble stabilization and algae removal), as well as coral disease and predator management[19,56]. Recommendations for restoration include considering local ecological and socioeconomic resilience factors during planning, particularly around the choice of site and coral species to restore[58]. Restoration should also prioritize lasting and effective impacts on reefs and their associated local economies.

However, coral restoration should be considered an additional effort and not a substitute for maintaining intact coral reef biodiversity. Current restoration efforts are expensive and have yet to be scaled to ensure long-term, substantial impacts[59]. These remain as key challenges for coral restoration efforts globally[60,61]. Nonetheless, some isolated examples have demonstrated improved resilience to bleaching[13]. A suite of international commitments is also underscoring restoration's importance by calling for increases and improvements of the practice on degraded reefs, including the UN Decade of Ecosystem Restoration, Target 2 of the GBF that calls for restoring 30% of all degraded marine and terrestrial ecosystems by 2030, and the Coral Reef Breakthrough. Global standards of practice are also being developed to translate decades of restoration work in terrestrial systems for coral reefs[56,61,62]. However, more scientific research on restoration methods, best practices, and effectiveness are needed to deliver broadly scalable solutions.

Scientists are also exploring ways to accelerate adaptation through interventions like selective breeding, hybridization, or introducing heat-tolerant algal strains to corals. Exploring initiatives like a global cryo preservation coral bank could safeguard genetic diversity if immediate restoration goals are unmet, serving as a long-term resource similar to the Global Seed Vault. Research organizations such as the Australian Institute of Marine Science have also made progress studying genetic interventions for coral resilience, including breeding and transplanting resilient corals as well as experimenting with assisted gene flow[63–65].

Studying mesophotic reefs, which are far less understood than their shallower counterparts, is important because they represent a significant portion of global coral reef habitat, play a crucial role in marine biodiversity and ecosystem services, and, growing in deeper waters, may be less exposed to heat stress from climate change now and in the future[66,67]. Mesophotic reefs are important for commercial fisheries and may possess unique adaptations to environmental stressors, which could provide valuable insights for coral conservation and restoration. Understanding these ecosystems is essential for developing effective conservation strategies across different reef depths.

Global engagement, cooperation and impact financing are essential to fund these interventions. Stronger collaboration between government agencies, private industries, conservation organizations, and local communities is needed for coordinated research strategies for reef conservation.

Environmental organizations can play a key role by supporting pilot restoration programs to test and evaluate new technologies in real-world settings. Additionally, scientists can develop standardized global monitoring protocols, which will allow for better comparison and aggregation of data on reef health and coral bleaching events (Fig. 1)

Case Study #1: The Red Sea

The Red Sea contains over 12,600 km² of coral reefs and over 265 coral species, making its reefs a global biodiversity hotspot. A series of studies found that corals in the Gulf of Aqaba (GoA), a northeastern extension of the Red Sea, exhibit remarkable resistance to rising water temperatures, surpassing the resilience of many corals in other regions worldwide[68–73]. This unique thermal resilience of corals from the GoA is hypothesized to result from the repopulation of naturally selected, heat-tolerant genotypes in the Red Sea following the last glacial maximum[72,74]. Consequently, the GoA is considered a thermal refuge for corals in the face of warming oceans. Nevertheless, the warming rate of the GoA is faster than the global average (nearly 0.5 °C per decade)[75]. Along with consistent long-term warming, there has been an increase in the intensity and frequency of extreme temperature events, known as marine heatwaves[76]. The first marine heatwave in the GoA was documented in 2015[77]. In 2017, two consecutive marine heatwaves resulted in fish mass mortality, although without recorded coral bleaching in the GoA[78]. Moreover, following a strong heatwave in 2021, common coral species demonstrated remarkable metabolic resilience[79].

Then during the fourth global mass bleaching event in 2024, the GoA experienced unprecedented thermal stress with a recorded 30 Degree Heating Weeks (DHW)—nearly double the previous local record in 2020 and marked by maximum water temperatures of 31.9 °C months[80,81]. DHW is an index for cumulative heat stress on coral reefs, with values above 20 DHWs historically associated with near-complete coral mortality[11,82]. Despite such extreme thermal stress, the impact in the GoA was relatively contained, with bleaching documented only in a small handful of species comprising about 5% of corals within the shallowest reefs (<5 m) in the northern GoA, and most affected corals having recovered within a few months[80,81].

This exceptional resilience presents an opportunity to safeguard at least one major coral reef ecosystem. However, this hope rests on the ability to protect the Red Sea reefs from local environmental stress and pollution. Studies show that local disturbances compromise coral's resilience to elevated temperature and determine the fate of corals under increased frequency and amplitude of marine heatwaves[15–17]. Increased urbanization and

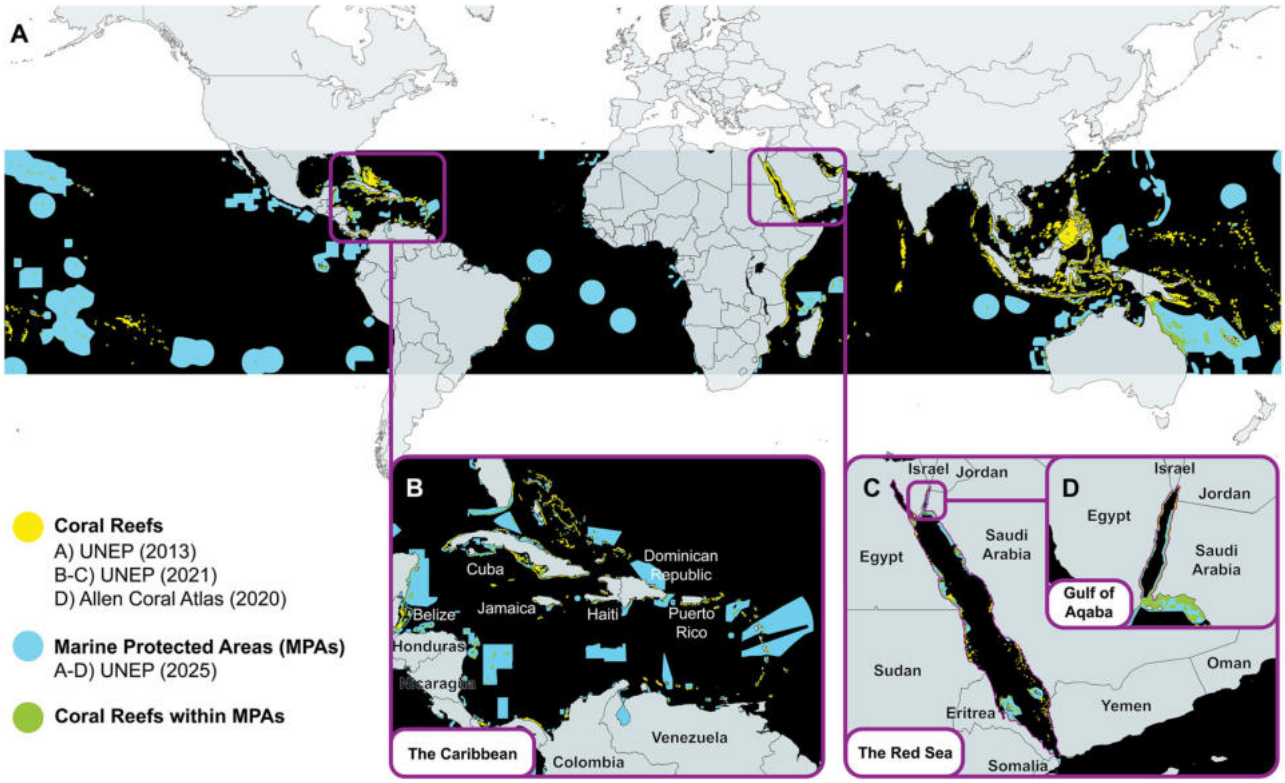

Fig. 1 | Global Map of Coral Reefs and Protected Areas. Maps of coral reefs across the globe (**A**) and in case study areas of the Caribbean (**B**) and the Red Sea (**C**), with an insert of the Red Sea's Gulf of Aqaba (**D**). The tropical oceans from latitudes 30° north to south, where virtually all coral reefs are located are denoted in black; other ocean regions have been omitted for clarity. Similarly, the Red Sea (**C**) and Gulf of Aqaba (**D**) are isolated by purple outlines, and all other surrounding reefs/MPAs have been omitted for clarity. Recorded coral reef and marine protected area (MPA) locations are denoted in yellow and blue respectively, with coral reefs located within MPAs denoted in green. Reef and MPA location sources for each panel are listed by letter under each category. Map.svg files from MapChart. Overlays sourced from UNEP 2013 (as available in Teh et al. 2013), UNEP 2021, Mittal et al. 2021, UNEP-WCMC/Protected Planet, and imagery from MapChart.net and Allen Coral Atlas[4,169–173].

industrialization of the coastal Red Sea may put reefs at immediate threat under climate change scenarios[83,84].

The GoA is bordered by Egypt, Israel, Jordan, and Saudi Arabia, and additional countries including Djibouti, Eritrea, Sudan, and Yemen surround other portions of the Red Sea. Political unrest in the Red Sea region often impedes regional-scale collaboration and conservation efforts for its transboundary reefs, putting the livelihood and future of millions of people in the region at risk[85]. Unilateral management of natural resources is often ineffective and may exacerbate environmental challenges, especially with common-pool resources. In the Red Sea region, where countries share natural resources, valuable ecosystems, and a history of conflicts (several of which are ongoing), transboundary environmental cooperation offers a pathway to improving livelihoods of numerous communities. Furthermore, as demand for tourism continues to grow, unsustainable ecosystem management poses a risk to local economies, especially in regions where ecological integrity is a key factor in destination choice. This underscores the importance of transboundary conservation efforts to sustain both livelihoods and economic stability[86]. It is key for standardized coastal zone management to be insulated from geopolitical conflicts (Fig. 2).

As illustrated by the systems map for the Red Sea (Fig. 3), workshop participants identified key leverage points for promoting coral resilience and cooperation. These include feedback loops linking citizen science, community-based monitoring, data-sharing platforms, and capacity-building mechanisms. For example, the loop connecting community participation and marine stewardship highlights the potential for economic incentives (e.g., eco-tourism) to reinforce public engagement and reef protection. These actionable pathways offer concrete strategies for regional implementation.

One important advancement for the Red Sea has been the 2024 International Coral Reef Initiative (ICRI) General Meeting in Saudi Arabia that resulted in the adoption of a resolution emphasizing the Red Sea's global significance[87]. Acknowledging the Red Sea as an "open-sky laboratory" for studying biodiversity and coral resilience to climate change, the resolution underscores its critical importance for over 28 million coastal residents who rely on these ecosystems for fisheries, tourism, and coastal protection.

Key elements of the resolution include:

1. **Regional collaboration:** Strengthen partnerships among nations to enhance the collection, monitoring, and sharing of coral reef data, fostering a unified approach to conservation. In parallel to the resolution, participants noted emerging political and societal interest in coral reef conservation across the region. One example is King Abdullah of Jordan, who used social media in 2023 to promote public awareness of the exceptional coral resilience in the Gulf of Aqaba, catalyzing national attention. Workshop discussions suggested that such top-down engagement could be further strengthened through trilateral community-based education programs between Egypt, Israel, Jordan, and Saudi Arabia, focused on school outreach, citizen-science diving, and co-developed curricula on reef protection. These programs were seen as opportunities to build shared environmental identity and trust through cross-border stewardship initiatives.
2. **Marine protected areas:** Expand the network of protected zones to achieve regional and global targets, such as the 30 by 30 initiative, safeguarding critical coral reef habitats.

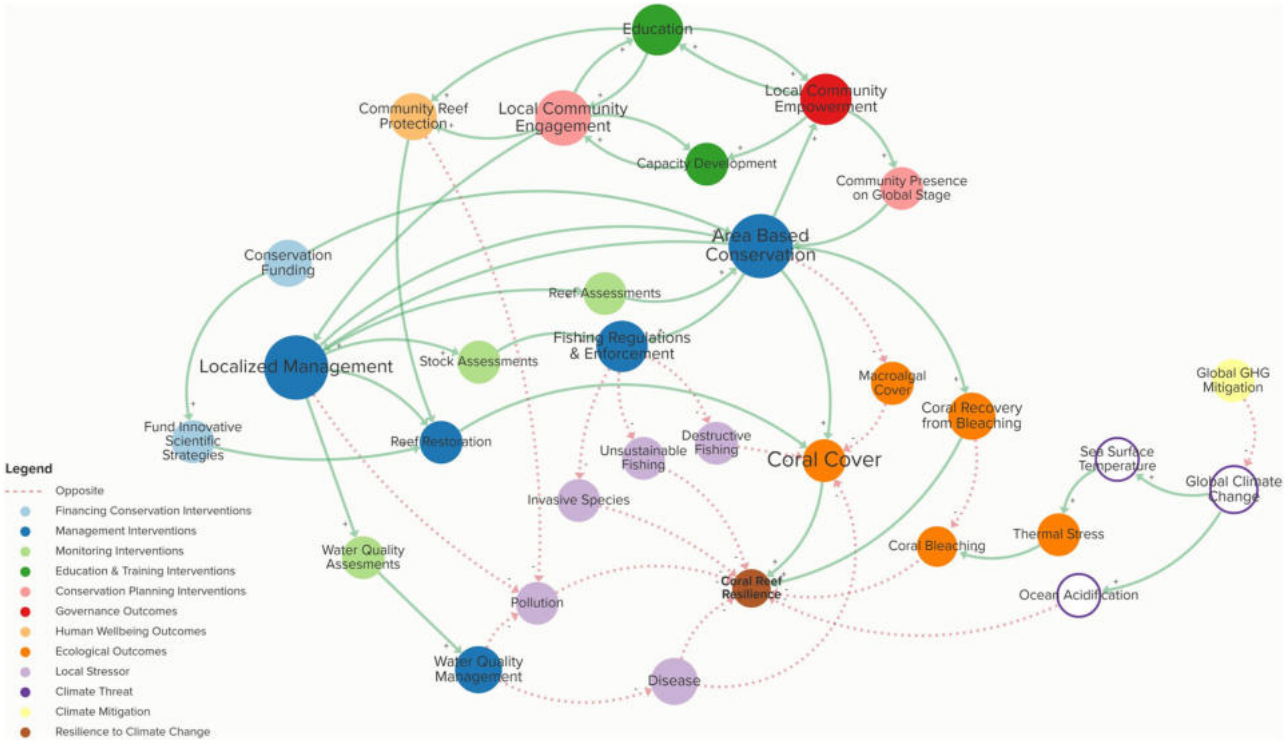

Fig. 2 | Systems map from the global breakout group. Arrows represent directionality, with solid arrows representing positive association between nodes and dashed arrows representing negative association. Size of node corresponds to the number of nodes leading to that node. Nodes are categorized by mitigating interventions, social and ecological outcomes, and climate threats and mitigation, all represented by color (see legend).

3. **Capacity building:** Empower conservation and restoration efforts by developing skills at all levels, from local communities to scientific and policy-making circles.
4. **Citizen science:** Promoting ocean literacy, community involvement, encouraging engagement with private industries, and fostering stewardship of marine resources.
5. **Community participation and economic empowerment:** Actively engage local communities in conservation and restoration efforts, emphasizing co-management of resources and sustainable practices. Promote diversified economic opportunities, such as eco-tourism, sustainable fisheries, and coral-friendly industries, to support livelihoods while reducing pressure on coral reef ecosystems.

This resolution provides a strong framework for protecting and restoring coral reefs in the Gulf of Aqaba and the broader Red Sea.

Furthermore, to secure the Gulf of Aqaba as a coral reef refuge, the four bordering nations of Jordan, Egypt, Israel, and Saudi Arabia must collaborate. As indicated in Fig. 3, international recognition and institutional cooperation were flagged as high-leverage opportunities for securing long-term resilience. Establishing a UNESCO World Heritage Site encompassing the GoA's uniquely resilient coral reefs, complementary to a proposal for reefs within Saudi Arabia[88], would:

1. **Promote conservation:** Provide legal and institutional frameworks for the preservation and sustainable management of coral reefs.
2. **Encourage international cooperation:** Strengthen collaboration between the four countries through joint research, monitoring, and enforcement efforts.
3. **Enhance global awareness:** Highlight the Gulf's unique role as a coral refuge, attracting global attention and funding for conservation efforts.
4. **Support local communities:** Develop sustainable tourism and alternative livelihoods to reduce dependency on extractive activities.
5. **Provide legal and institutional framework for long-term protection**

Steps toward securing world heritage status may include:

1. **Scientific documentation:** Consolidate existing research on the GoA's coral resilience and biodiversity, highlighting its global importance.
2. **Regional agreement:** Engage stakeholders from Egypt, Israel, Jordan, and Saudi Arabia to agree on boundaries, governance, and management objectives.
3. **UNESCO nomination:** Prepare and submit a comprehensive nomination dossier that aligns with UNESCO's criteria for natural heritage sites.
4. **Adaptive management plans:** Develop and implement adaptive management strategies addressing both regional and local stressors.
5. **Capacity building:** Train local and regional personnel in reef monitoring, enforcement, and eco-tourism development.

Establishing the Gulf of Aqaba as a coral reef refuge will serve as a model for other regions, showcasing how international cooperation can safeguard critical ecosystems. The GoA can also serve as a living laboratory for studying coral resilience and informing global strategies for coral restoration and protection.

In conclusion, the Gulf of Aqaba represents a beacon of hope for coral reef conservation in an era of climate uncertainty. By protecting it, studying its unique resilience, and fostering regional collaboration, we can ensure the long-term survival of this critical ecosystem and its invaluable contributions to biodiversity, science, and human well-being locally and globally.

Case Study #2: Caribbean

Caribbean coral reefs provide countless ecosystem services for the 40+ million people that call the region and its 7000+ individual islands home. In addition to non-monetary benefits, coral reef tourism in the Caribbean dominates the local economies of the region and generates ~ $5.7 billion basin-wide per year (>10% of total regional GDP)[89], and coral reefs contribute hundreds of millions of dollars annually to fisheries in the region[90]. The economic benefits of coral reefs to some Caribbean countries can total 14% of GDP[91]. Despite the high costs of restoration, cost-benefit analyses have identified that the cost of reef

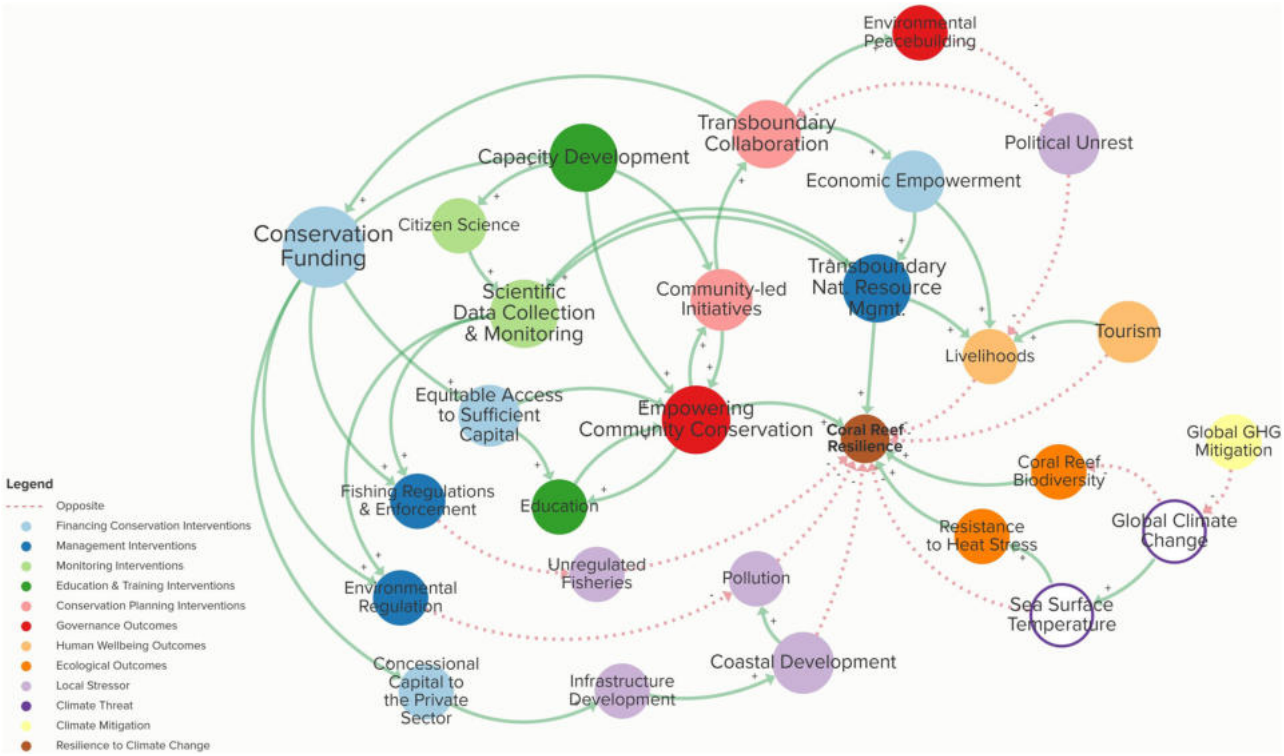

Fig. 3 | Systems map of significant actors and influences on coral reef resilience in the Red Sea region. While facing global and local stressors, reef conservation in the Red Sea can be bolstered with regional collaboration, marine protected areas, capacity building, citizen science, community participation, and economic empowerment. Arrows represent directionality, with solid arrows representing positive association between nodes and dashed arrows representing negative association. Size of node corresponds to the number of nodes leading to that node. Nodes are categorized by mitigating interventions, social and ecological outcomes, and climate threats and mitigation, all represented by color (see legend).

restoration in some parts of the Caribbean is outweighed by the benefits of coastal protection alone[92].

However, the Caribbean has been subjected to a range of pressures including poorly regulated tourism and coastal development, pollution, overfishing, invasive species, disease, hurricanes, and climate change induced warming that have reduced live coral cover in the region from 50% fifty years ago to 10% today (Fig. 4)[30]. The Caribbean is one of the most vulnerable regions of the world to anthropogenic climate change, yet is one of the smallest contributors to fossil fuel emissions. Future warming here is projected to amplify local stressors, especially hurricanes and coral bleaching[93,94]. Caribbean coral reefs are at high risk from extreme hurricanes that are increasing in severity, such as Hurricanes Irma and María (2017) that caused simultaneous mechanical destruction of corals, altered seawater chemistry, and buried reef-building corals under rubble and sediment loads in the northern and northeastern Caribbean[95].

For this region, the systems mapping approach identified a subset of tangible action points that are key to promoting ecosystem health and reef resilience (Fig. 4): (1) collaborative spatial planning and management; (2) empowerment and mobilization of local communities around reef resilience; and (3) equitable access to sufficient financial capital for reef management. Additionally, the Caribbean is politically complex, with 35 recognized entities including 22 countries and 13 overseas territories or dependencies with Caribbean coastlines. Consequently, any collective effort to advance coral resilience across the region requires significant political coordination. Such coordination could enable the implementation of the identified action points discussed below: (i) collaborative spatial planning and management, (ii) empowerment and mobilization of local communities, governments, and NGOs, and (iii) equitable access to financial capital.

First, regarding collaborative spatial planning and management, unsustainable coastal development and deforestation is a major stressor to Caribbean coral reef ecosystems[30]. Coastal sedimentation associated with deforestation, other types of land-use conversion, and dredging increases the sediment, nutrient, and other toxic pollution burdens on reefs[96]. At sea, overfishing of predatory and herbivorous species in the Caribbean contributes to trophic cascades that lead to ecosystem destabilization and algae overgrowth[30,97,98]. Addressing these issues requires ecosystem-based approaches that address multiple stressors such as coastal and marine spatial planning (Fig. 4, Collaborative Land & Ocean Planning). This includes coastal development plans to address land-based sources of pollution and sedimentation and area-based conservation. However, only 20% of land and 40% of coral reefs in the Caribbean are protected (especially important ecosystems may call for higher protection than global targets of 30%)[99–101]. And like most MPAs around the world, the majority of that area may lack the financial, logistical, and personnel resources to be effectively managed, while also lacking the necessary legal frameworks. Only 4.6% of reefs in the Caribbean are included within highly or fully protected areas that provide the most effective protection[43,101].

Considering the transboundary nature of watersheds, ocean circulation, and migratory fish stocks, sustainable resource management and spatial planning are shared responsibilities for the region and would be best served by collaborative, multinational approaches that consider the transboundary implications of both marine and terrestrial protected area networks. A good example of regional coordination is the Healthy Reefs Initiative that works within the Mesoamerican Reef System (MAR) spanning the Caribbean waters of Mexico, Belize, Guatemala, and Honduras[102]. Here, the Healthy Reefs Initiative, which comprises over 70 local and international NGOs, academic, and governmental institutions, has been catalyzing conservation for two decades, as well as other transboundary initiatives such as the Mesoamerican Reef Fund (MAR Fund). Another example is the Caribbean Challenge, led by The Nature Conservancy, where

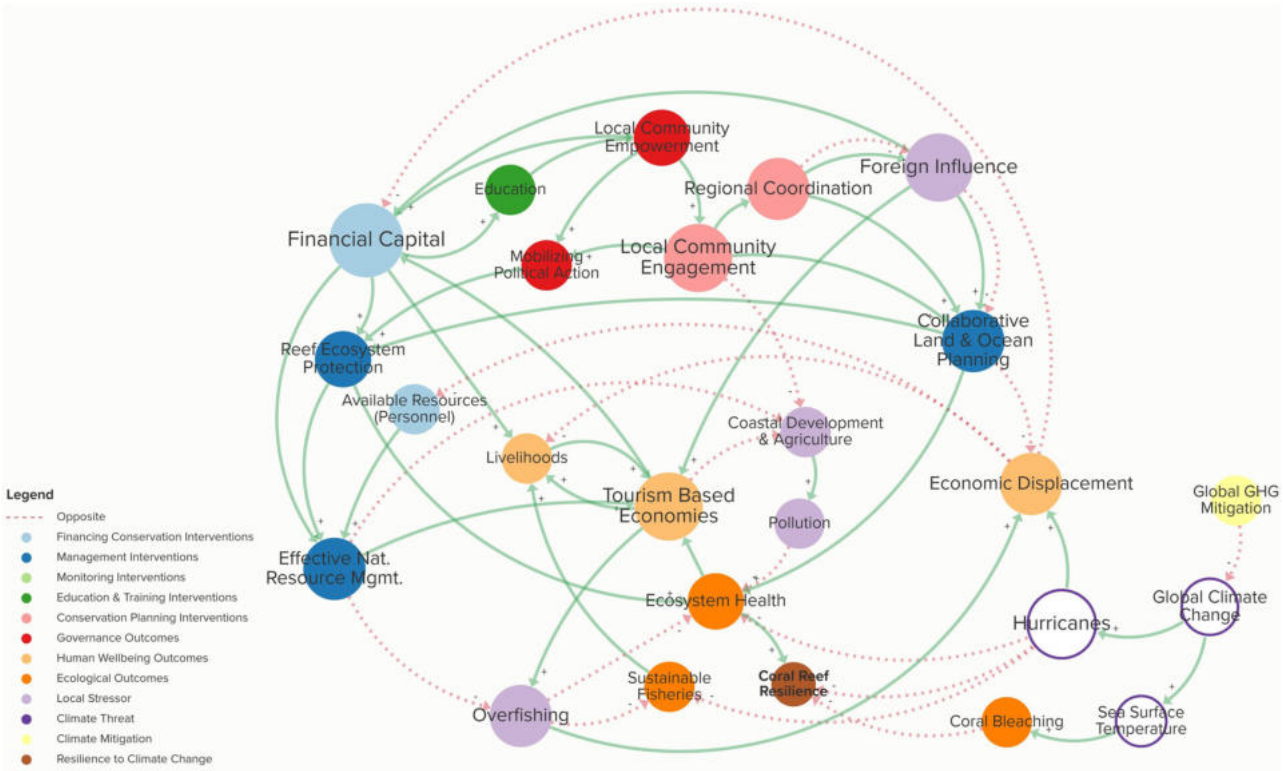

Fig. 4 | Systems map of significant actors and influences on coral reef resilience in the Caribbean Sea. While facing global and local stressors, reef conservation in the Caribbean region can be bolstered with collaborative spatial planning and management, the empowerment and mobilization of local communities, governments, and NGOs, and equitable access to financial capital. Arrows represent directionality, with solid arrows representing positive association between nodes and dashed arrows representing negative association. Size of node corresponds to the number of nodes leading to that node. Nodes are categorized by mitigating interventions, social and ecological outcomes, and climate threats and mitigation, all represented by color (see legend).

11 Caribbean countries committed to protect 20% of their coastal waters by 2020 through various forms of capacity support[103]. However, while the Caribbean Challenge sets a model for international coordination, these types of efforts must be scaled to include more countries to sufficiently protect the Caribbean.

Second, on empowerment and mobilization of local communities, governments, and NGOs, healthy coral reefs are critical for the social and economic wellbeing of many communities throughout the Caribbean basin[90,91]. While tourism is a key economic driver in the region, attracting significant foreign investment, it has also been a driver of overfishing, unsustainable coastal development, and pollution[30]. Additionally, foreign investment in industries like agriculture and tourism can incentivize corruption, a lack of political will to address unsustainable coastal tourism development, and the capture of economic benefits by powerful elites, leading to social injustices and harm in many areas[104–109].

Empowering and mobilizing local actors by increasing their role in reef governance can enable them to counter negative influences from foreign capital (Fig. 4, local community engagement). Additionally, many reef-dependent Caribbean communities have shown support for coral reef management when directly involved in governance processes[110,111]. Local actors and organizations have also advanced sustainable reef management and rights advocacy and possess rich contextual knowledge around coral reefs and successful management approaches that can be applied to other locations[111–114]. Therefore, fostering stronger regional coordination between community stakeholders, local NGOs, and policymakers can advance sustainable practices, promote transparency, and address shared challenges.

At the regional scale, the Caribbean Large Marine Ecosystem Project (CLME; 2009–2014 and revamped 2015–2020 as CLME+) is an example of an initiative which developed a framework for regional ocean governance in the Wider Caribbean Region[115]. The framework focused on accommodating the geopolitical realities of the region and the need for local participation in governance to outline interventions. The resulting comprehensive Strategic Action Program served as a roadmap for sustainable living marine resources management through strengthened and consolidated regional cooperation[116]. Continued coordinated efforts around knowledge sharing that focus on organizational engagement could therefore serve to unify countries across the Caribbean as a single entity with shared reef resources in international policy forums. This type of political coordination across Caribbean nations on the international stage can also further empower local and national organizations by building political alliances for global political platforms and negotiations, which can provide Caribbean nations with greater agency when acting collectively rather than alone.

And third, for equitable access to financial capital, the mobilization of Caribbean communities around reef stewardship and collaborative spatial planning necessitates not only intellectual capital but also the financial capital necessary to coordinate, implement, and support reef management strategies (Fig. 4, Financial capital). Unfortunately, like ocean conservation globally[117,118], the financial resources being allocated to conserving reefs in the Caribbean are severely inadequate[119]. Given the number of small island states in the Caribbean, multinational efforts to raise and allocate more substantive funding reflective of the socioeconomic importance of coral reefs to the region can help strengthen the collective efforts for building regional resilience. For example, the Bridgetown Initiative is a finance reform initiative aimed at reducing the climate debt burden for developing nations by increasing trust- and climate "bail-out" funding from international development banks as well as funding reconstruction efforts following climate-related disasters in "at risk" communities[120]. Alongside raising funds, the focus on "at risk" communities can help

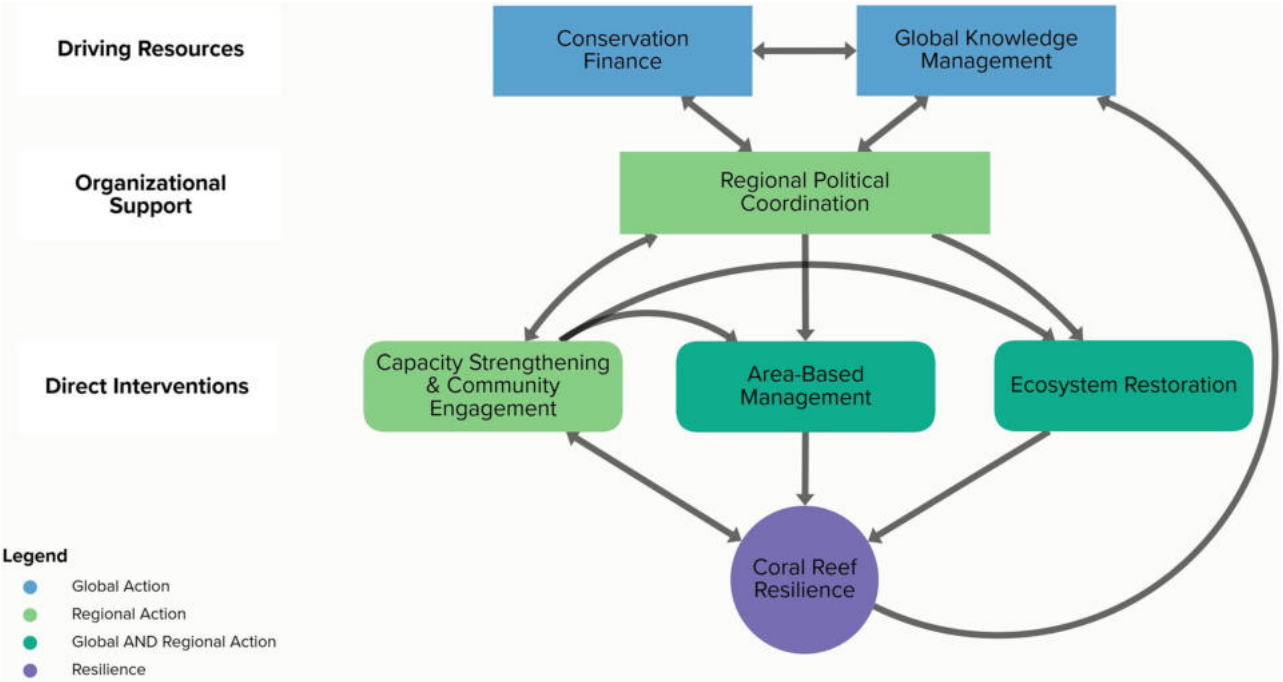

Fig. 5 | Holistic framework for international cooperation and transboundary management for building coral reef resilience. Arrows reflect flows of support, communication, and information across elements, which include scientific and traditional knowledge that originates at local levels but is consolidated and re-disseminated at the global level.

direct funds in a more equitable manner than current markets and economic systems would typically allow. Another example of capital allocation is Belize's successful Blue Bond program, which reduced national debt by 12% while securing ~$180 million of long-term financing for ocean conservation through grant funding to national NGOs, government reef management agencies, and results-based private financing[121].

However, only three of the 35 Caribbean countries including Belize have benefitted from such a transaction[122,123], and these initiatives need to be rapidly scaled to support the region. The pursuit of such regionally focused initiatives will allow smaller states, which independently might be unsuitable for institutional investment due to small economies and informal sectors[124], to benefit from innovative conservation finance tools. Regional financial incentives might also prevent perverse economic incentives and corruption and encourage equitable access to funds in this politically decentralized region, provided such mechanisms and funds are managed transparently and equitably with input from all countries and other relevant stakeholders. Regionally focused environmental funds, such as the Caribbean Biodiversity Fund and Mesoamerican Reef Fund, are key partners in managing and allocating structures like public funds used in Blue Bonds and Debt-for-Nature Swaps. Networks like the RedLAC Congress or a new SIDS CTFs community of practice (for which author JB participated in a kickoff meeting during the third United Nations Ocean Conference in June 2025) can support regional coordination by linking environmental funds across Latin America and the Caribbean and SIDS respectively.

In conclusion, effective regional coordination in the Caribbean is essential, especially as climate change and local pressures outpace adaptive capacity. These challenges are compounded by unequal resources, governance gaps, and competing agendas across conservation, tourism, and the blue economy. Strengthening and scaling efforts like Healthy Reefs for Healthy People and the Bridgetown Initiative can help address these issues. A growing global push for a sustainable blue economy—backed by organizations like the OECD—presents an opportunity to direct funding toward reef conservation, which underpins regional economies. By leveraging existing platforms, Caribbean actors can build capacity, share solutions, and secure a stronger, more unified voice in global climate and biodiversity efforts.

Discussion

The global and two regional analyses presented above had several commonalities as well as key differences. Based on these outputs, we grouped the recommendations provided into a series of pathways for building coral reef resilience through both global and regional action, and how these connect as part of a larger holistic approach for international and transboundary efforts to support coral reef resilience (Fig. 5). There are both actions that directly support resilience such as area-based conservation and restoration, as well as actions that build the supporting framework such as finance and science. Below we discuss how these pathways are relevant, support one another as part of a holistic approach, and apply to global or regional action.

Driving resources includes securing the financial needs and technical knowledge to support coral reef conservation and build resilience. Global action for building coral reef resilience begins with resources that drive coral reef conservation efforts, such as conservation finance, which includes the raising and allocation of financial resources that support all other aspects of this holistic, global approach. Both the Red Sea and Caribbean case studies identified the need for access to financial resources. The Red Sea has some high-income countries such as Saudi Arabia and Israel that can provide finance from within the region, although several Red Sea countries such as Sudan and Eritrea are Least Developed Countries. Globally, coral reefs are often located in developing countries and Small Island Developing States (SIDS), so most will rely on the international community to help source funds or provide capacity support to help unlock financing as demonstrated by several prominent coral reef and marine conservation finance initiatives[34,118,121,123,124].

For regions comprising mostly low- and middle-income countries, finance primarily needs to be addressed at the global level and delivered to regional financial management bodies (e.g., regional funds acting as conduits) to support direct and coordinate actions for reef resilience. Under this dynamic, the global community plays the role of supplying funds, with regional level governance developing the necessary capacity and

institutional frameworks to receive and distribute funds. Platforms such as the Global Environment Facility, which hosts the Global Biodiversity Framework Fund, and the CBD, through which countries recently agreed to a global biodiversity finance roadmap as an outcome of COP 16 and establishment of a new "Cali Fund" that raises contributions from the private sector[125], are instrumental bodies for raising and delivering funds.

Finance is critical to supporting science, as referenced in the global breakout group's outcomes. Finance also benefits from science through improved understanding of ecosystem services and marine resources that can be the basis of innovative financial mechanisms. Examples include leveraging the value of coral reefs for coastal protection to support mechanisms such as coral reef insurance funds, offsets or credits for carbon sequestration in connected ecosystems such as mangroves or seagrass beds, biopharmaceuticals from coral reef genetic resources, and others[5,34,124,126–130].

Whereas conservation finance reflects the raising, management, and allocation of financial resources, global knowledge management reflects the gathering, synthesizing, and dissemination of the world's collective understanding of coral reef ecosystems and conservation. Science, for example, is critical for identifying, developing, testing, and applying innovative approaches to support resilience. Area-based management tools such as MPAs, and increasingly forms of coral restoration, are examples of widely applied approaches that have been informed by science needed for successful implementation and long-term management[43,56]. Other approaches such as coral reef engineering (e.g., hybridization) discussed in the global breakout group are also being investigated and may become more available and increasingly applied to support resilience as basic science on these matters advances.

More mainstream scientific knowledge must also be equally accompanied by other knowledge sources that offer indispensable experience in coral reef conservation, including from Indigenous Peoples and Local Communities. For example, whereas MPAs are the subject of frequent research among mainstream science and sometimes viewed as 'western' inventions, area-based management including spatial closures have long-standing Indigenous roots in parts of the world such as Oceania[131]. Documented cases of community- or co-managed MPAs, locally managed marine areas, and other forms of community-based management around the world have further supported the value of traditional knowledge for global ocean management[112,131–136]. "Two-eyed seeing," a framework for facilitating complementarity across Indigenous and other forms of knowledge (including mainstream science), is one of several examples of models that help the different knowledge streams around the world work together[135].

A robust global knowledge base that integrates diverse sources of experience and expertise—from scientific to traditional—can maximize knowledge exchange and drive coral reef conservation and climate resilience from local to global scales. To fully leverage the best available understanding of coral reef systems and translate it into effective action on the water, global knowledge management must be built from the bottom up. Accordingly, while science and knowledge management are positioned at the global level (as shown in Fig. 5), the arrows in Fig. 5 illustrate the bi-directional flow of support, communication, and information. This flow reflects the consolidation of knowledge rooted in more local scientific and traditional practices, synthesized at the global level, and shared back to inform action worldwide. To facilitate local-global knowledge exchange, it is also the responsibility of the global community to ensure local efforts, ideas, and initiatives are supported and further enhanced.

With seascapes and coral reef regions often divided amongst several countries, regional political coordination (in the form of regional political bodies or alliances for conservation) is vital to ensuring that coral reef management accounts for the transboundary nature of these ecosystems. As part of a comprehensive multinational framework, regional political coordination plays an important role in moving resources from the global community (or in some cases across regions), including finance and scientific knowledge, to support the implementation of more direct local and regional measures including area-based management efforts, restoration, and capacity strengthening in an equitable and coordinated approach. This includes the potential institutional frameworks for supporting or applying conservation initiatives such as a regional or seascape level transboundary MPA network. Furthermore, political coordination can also foster bottom-up communications such as advocating for finance or transferring knowledge from respective regions to the global community.

Both the Red Sea and Caribbean case studies identified concrete benefits or priorities for regional political coordination for multinational approaches. The Red Sea case and the ICRI Red Sea resolution emphasized the benefits of political coordination to support scientific knowledge and data sharing as well as joint efforts for monitoring and enforcement, and the Caribbean case showcased Healthy Reefs for Healthy People, the Mesoamerican Reef Fund, Caribbean Challenge Initiative, and Caribbean Biodiversity Fund as examples of influential transboundary initiatives. However, while there were some commonalities around political coordination across the Red Sea and Caribbean cases, the meaning of political coordination, including its intended purpose and desired effect for coral reef health, also differed across these two examples.

The Red Sea, as compared to the Caribbean, is a smaller region of fewer, larger neighboring countries with a longer history of cultural and political interaction but also direct conflict that has stymied collaboration on many levels. Country economies vary from low-income countries on mainland Africa to wealthy countries such as Saudi Arabia and Israel. Political coordination for reef conservation should advance agreements on governance and management objectives, as well as potential coordination around the nomination of a multinational UNESCO World Heritage Site. The Red Sea systems map (Fig. 3) further illustrates how centralized political will, when aligned with scientific cooperation and public engagement, can support reef governance in regions affected by geopolitical instability.

When compared to the Red Sea, the Caribbean is a politically more disparate and decentralized region with 22 countries and 13 territories, many of them small island states with smaller economies where there has historically been limited interaction and communication across nations. Considering the decentralization and capacity of Caribbean economies, the Caribbean case study also found bottom-up political coordination offers important benefits. By creating a unified regional voice, Caribbean nations can strengthen their agency in international forums on climate and biodiversity, including efforts to advocate for conservation financing.

Direct interventions include regional or sub-regional actions that directly support coral reef resilience.

One example is area-based management—both marine and terrestrial—which was referenced as an important area of action for supporting coral reef resilience highlighted at both the global level and for the two regional case studies. The global community primarily supports area-based management through the creation, monitoring, and oversight of policies directed at tools such as MPAs. Examples also referenced in the global breakout group's outcomes include UN SDG 14.5 (protect 10% of the ocean by 2020) and, more recently, Target 3 under the CBD Global Biodiversity Framework that calls for protecting 30% of land and sea by 2030[32,33]. While the global community helps create policies and targets that help direct area-based management, the actual implementation of PA networks is best directed at the regional level. The global community can further support these efforts by providing guidance and resources, including establishing best practices, that can help drive the implementation of PAs and other spatial management tools at more local levels in efforts to meet national commitments[43,136]. Regional coordination in spatial planning, PA designations, management, and enforcement is further needed to provide comprehensive seascape or landscape scale protection for transboundary ecosystems including coral reefs and watersheds[137,138]. Examples include the Mediterranean Protected Areas Network (MedPAN) which among other initiatives could be a model for regional MPA networks in the Red Sea and Caribbean[139,140]. Additional tools such as international designations of important sites can also be helpful for area-based management (e.g., UNESCO World Heritage Site

designation) to rally political support and potentially funding for the protection of these key areas[141–144].

Ecosystem restoration is another example of a conservation tool or approach that, like spatial management, benefits from guidance, leadership, or direction from the global community but requires more local or regional efforts for implementation. One example is Target 2 from the Global Biodiversity Framework, as discussed in the global breakout group that sets a global target for ecosystem restoration efforts. While coral reef restoration remains expensive and challenging to scale via current methods[59], these policies or targets at the global level can be helpful for raising and allocating the necessary resources to advance and mainstream coral restoration practices to achieve the necessary scale. Other practices, in addition to restoration and area-based management, may also become more widely utilized as the science investigating novel approaches continues to develop. Restoration projects can also deliver vital benefits for public engagement and education for coral reef conservation, such as through citizen science or other opportunities for hands-on participation with coral reef restoration projects.

A third form of direct intervention highlighted by the workshop was capacity strengthening and community engagement. Capacity refers to the knowledge, skills, and institutional ability of conservation practitioners, Indigenous Peoples and Local Communities, and other stakeholders to design, implement, and manage activities that support reef resilience, including area-based management and restoration. Capacity strengthening involves enhancing this ability through education, peer-to-peer learning, access to funding and tools, and other forms of support. It is considered a direct intervention because it enables local actors to lead or contribute to conservation efforts. Community engagement also includes the upward flow of knowledge, facilitated by regional political coordination, to allow more local knowledge and experiences to inform global policies. While capacity strengthening and community engagement is primarily developed through regional efforts, the global community also has a responsibility to provide platforms for this engagement.

In the Caribbean case study, widespread cultural awareness of the importance of coral reefs, and some isolated cases of successful local management were evident. However, greater international communication and political coordination could promote this knowledge more widely. Greater local economic agency is also essential in a region where foreign investment, particularly in tourism, often dominates.

Economic empowerment was also highlighted in the Red Sea case study. This included the benefits of diversified reef-based economies aligning with sustainable management, and training and employing community members as conservation practitioners to support monitoring, protection, and restoration, alongside historic efforts for citizen science in the region. In addition to economic diversification, workshop participants recommended scaling community monitoring through low-cost, accessible tools such as CoralWatch, simplified water quality testing kits, and mobile applications for reef condition reporting. Such citizen-driven monitoring efforts could be integrated into regional databases, jointly maintained by NGOs and government agencies from the four bordering GoA nations. This approach was seen as especially valuable for promoting local ownership, addressing capacity gaps, and enhancing transparency in transboundary reef management.

Furthermore, community leadership and engagement is important not only for effective conservation, but for advancing social equity, human rights, and environmental justice. Conservation has historically, in many contexts, excluded local and Indigenous communities, including via restricted access, imposing external priorities (including neo-colonialism), and perpetuated social harms[131,145–147]. Actively engaging communities as full partners in conservation—including recognizing their rights, knowledge, and priorities—is essential for creating durable and just outcomes for both people and ecosystems that avoid repeating exclusionary practices of the past.

Building on this, it is also important to reflect on the complementary roles of actions at global, regional, and local levels. Our review highlights the global community's critical role in shaping conservation by integrating scientific and traditional knowledge into targets and commitments. Policies developed at the global level, such as through the Global Biodiversity Framework, help guide conservation interventions regionally. Encouragingly, recent global commitments increasingly reflect priorities identified through our social-ecological approach, including stronger emphasis on area-based protection, ecosystem restoration, sustainable finance, and Indigenous and Local knowledge. The alignment with outputs from our workshop, compiled by a diverse coalition of coral reef experts, suggests that global policies can incorporate best available science and regional knowledge. Global policies could drive coral reef conservation if effectively enforced. The global community can also help mainstream emerging tools, such as coral hybridization and protections for mesophotic reefs, as their scientific foundations strengthen.

The framework for regional and global efforts to build coral reef resilience also highlights shared priorities across regional case studies, such as the need for well-designed area-based management, community engagement, and climate change-focused restoration. However, effective implementation of conservation depends on the regional context, even for similar ecosystems like coral reefs. For example, Caribbean MPAs often rely on international resources due to smaller economies spread over many islands, while the Red Sea—which still requires international support—can benefit from wealthier countries in the region like Saudi Arabia and Israel. Both regions face political coordination challenges, but in different forms: the Caribbean must build communication and alliances among SIDS with limited formal ties, while the Red Sea faces coordination amid conflict. Community engagement also differs: Caribbean efforts elevate existing reef knowledge, while Red Sea initiatives focus more on building awareness through community engagement, such as with citizen science and global designations like a UNESCO World Heritage Site. These differences may reflect that the Caribbean's coastal populations often depend heavily on coral reefs for tourism[2], storm protection[3,148,149], fisheries[4], and other benefits, whereas in the Red Sea, although some communities rely on reef services such as tourism in Egypt[150], most countries have more diversified economies and a larger proportion of their populations and political centers are physically and culturally more distant from coastal regions.

Ultimately, regional differences underscore the need for tailored approaches to transboundary reef management. Regional institutions can play a key role in interpreting global guidance and translating it into action that aligns with each region's social, political, and environmental realities.

A broader goal of this work is also to demonstrate how knowledge exchange among experts can help prioritize needs and actions within a clear framework. The workshop and subsequent case study groups brought together researchers, practitioners, and funders with global and regional experience in coral reef conservation, as well as expertise spanning topics from coral physiology to sustainable finance. This diversity of knowledge was applied through plenary sessions and cross-group discussions to enhance the participatory systems mapping process. The resulting case studies offer a model for how global and regional insights can be combined to guide conservation strategies. This approach can be replicated for coral reef management in other regions, and more broadly across marine conservation.

Conclusions

Many of the key themes emphasized in this paper, including the urgency of the climate crisis, coral reef resilience, and the need for measures such as area-based management, community engagement, and financial resources for conservation, have been recognized in the coral reef conservation discourse for decades[151–154]. Calls for regional action and cooperation to support coral reefs have also been made since—at least—the original ICRI Call to Action in 1995[155]. But in practice, these have rarely been implemented beyond a few notable examples, some of which have been referenced or discussed, such as the Mesoamerican Reef Fund and Coral Triangle Initiative.

What this work contributes is a cohesive and structured framework that explicitly links six levers for coral reef conservation into an actionable roadmap bridging global, regional, and local scales. By situating long-recognized principles within the context of the latest science and current international policy environment, we propose how they can be advanced through concrete strategies that address today's challenges.

This work also introduces a novel case study approach that applies participatory systems mapping to analyze social-ecological systems and prioritize intervention points for action. Through the comparative cross-analysis of two ecologically and politically distinct regions—the Red Sea and Caribbean—we demonstrate how shared global principles manifest differently depending on regional governance, socioeconomic context, and ecological realities. This side-by-side analysis not only highlights universal pathways for supporting coral reef resilience, but also underscores the importance of tailoring interventions to regional circumstances. This comparative application of systems mapping to transboundary reef conservation is, to our knowledge, unprecedented in the literature and offers a replicable model for other regions.

The field's understanding of coral reef responses to climate change has evolved substantially over recent decades. When the first recorded global bleaching event occurred in 1998, the drivers, mechanisms, and patterns of coral resistance and resilience were little understood. Since then, decades of research—much of which has been highlighted in this paper—have uncovered the genetic, ecological, and oceanographic factors that underlie the resilience of some reefs, exemplified by the Red Sea and, in particular, the Gulf of Aqaba that was a central focus of this study. This growing body of evidence highlights both the urgency and the opportunity to protect such refugia before they are lost to more local threats.

In parallel to our developing knowledge of climate change and coral reefs, international policy pathways to act on these issues have also changed. Agreements such as the Kunming-Montreal Global Biodiversity Framework, outcomes that have arisen from the framework, such as the Cali Fund, and other global initiatives for coral reef and biodiversity conservation, such as the Global Fund for Coral Reefs, have created mechanisms and targets that did not exist when many of these concepts were first articulated. This work integrates the latest understanding of climate change and coral reefs with these evolving policy instruments to show how conservation actions can be adapted to align with both ecological contexts and political opportunities while providing a renewed call to action for fundamental progress in marine conservation, long called for by experts.

However, academic literature such as this paper is insufficient on its own to change the narrative shaped by decades of insufficient action. Ensuring that research findings influence policy, practice, and public awareness requires deliberate efforts to engage beyond the academic sphere. Accordingly, our team of authors has made active efforts to communicate this work to a broader audience by complementing this academic article with a publicly accessible whitepaper for non-technical audiences[156]. We have also shared the findings through a side event at the third UN Ocean Conference in Nice, June 2025. We have plans to continue engaging diverse audiences as well as a wider network of practitioners, particularly from organizations currently or looking to support transboundary coral reef conservation.

Additionally, addressing the global coral reef crisis requires diverse, multidisciplinary teams that reflect the regions and communities affected, a point supported by recent work highlighting the importance of inclusive authorship in coral reef science[157]. This paper embodies such an approach, bringing together authors from varied disciplines, institutions, and geographies, and integrating regional knowledge and perspectives into the analysis and recommendations. We hope this work contributes not only actionable pathways for conservation, but also a model for how inclusive, collaborative research can bridge the gap between knowledge and implementation in support of coral reef resilience

Coral reefs remain in a state of emergency. But by coordinating global leadership with regional and local action, informed by both decades of accumulated knowledge and today's refined tools and policies, we can move closer to the outcomes the coral reef conservation community has long aspired to achieve.

Methods

This paper presents the results of a workshop held at Stony Brook University in June 2024, titled, "Blueprints for Resilience: A workshop on coral reef resilience, conservation, and charting a roadmap for scaling effective conservation interventions for climate-resilient reefs." Inspired by work in the Red Sea, the workshop's primary aim was to integrate diverse expert insights to fortify coral reefs against escalating threats from climate change through global and regional action. The workshop priorities included:

1. Participatory systems mapping: Participatory systems maps are graphical representations of a system created by stakeholder groups. Connections are directed from one factor, or node, to the following node, representing the flow in these systems. Participatory systems mapping is an interdisciplinary approach which can successfully engage stakeholders from diverse disciplines and backgrounds[39–41,158,159]. In this case, we brought together workshop participants to map coral reef systems of interest as a way to understand pathways which either bolster or hinder coral reef resilience. In case study breakout groups, participants identified threats to and mitigators of coral reef resilience. They visually mapped the connections between the variety of threats undermining coral reef resilience, the mechanisms through which these threats occur, and the mitigating conservation actions that can be addressed to support resilience within each focal area.
2. Prioritization: Based on the outputs from the participatory systems mapping work, participant groups prioritized threats to coral reefs and further developed action plans to mitigate these threats, important linkages in the system, and/or conservation actions that should be pursued to scale globally, considering a balance of potential impact, feasibility, and other factors.
3. Development of an action plan: Each group then developed action plans to address the previously identified priorities. Questions considered included: What is needed to achieve goals? Do they require action on a global, regional, or local scale (or cross-scale)? What are the roadblocks to achieving them that need to be addressed, and do they require additional financial investment, political attention, or social interest?

The process for the participatory systems mapping was adapted from the RAPID Outcome Mapping Approach (ROMA) policy engagement tool process for developing a collective theory of change that was facilitated by authors DAG and DIG[160]. The workshop participants were assigned to one of three breakout groups (Global, the Red Sea, and the Caribbean) and were asked to define "coral reef resilience to climate change" in their own words to facilitate a collective understanding of the overall goal. Using sticky notes, participants then identified what they believed were the three most important social and ecological factors affecting coral climate resilience for their scope or region, and described how each driver affected resilience. Each breakout group then collectively discussed and grouped their factors into similar themes, identifying how they directly or indirectly affected resilience, as well as their effect on any other factors identified.

Each group then reported their results to the wider workshop as a narrative before returning to their breakout groups to create a systems map, placing coral reef resilience in the center and arranging the various factors around it with lines and arrows to show the relationships between components. For the components that represented threats or problems, the facilitators encouraged participants to add the root drivers of these problems. For factors that were solutions, participants added the enabling factors needed for the solution to be effective. Participants then reviewed and reflected on the maps before adding any missing components, connections, feedbacks, or other factors to complete them.

Within the systems maps, positive and negative feedback loops were very important for influencing change in a system, with the potential to

amplify positive or negative elements, or negate elements as a counter-balancing loop. Underlying factors in feedback loops can represent common root causes that have a disproportionate positive or negative impact on the system, including factors that affect multiple other elements in the system. Combined, feedback loops and underlying factors identified in the social-ecological systems represent potential levers that can be used to exert a strong influence on the system, and coral reef resilience for each breakout group's scope.

Data availability

No new data were generated or analyzed during this study. The spatial data used to produce Fig. 1 are publicly available from the sources cited in the figure caption.

Code availability

Not applicable.

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Author contributions

K.K. was a co-PI on the grant that supported this work, conceptualized the 2024 workshop, and helped lead the drafting of the manuscript. J.B. led the workshop planning and execution, led the drafting of the manuscript, and produced Fig. 5. M.F. was the PI on the BSF portion of the NSF-BSF grant and led and drafted the Red Sea breakout group case study. D.I.G. helped design the workshop methods (e.g., the participatory systems mapping approach), helped facilitate and created the digital systems maps based on the hand-drawn maps from the workshop (Figs. 2–4). D.A.G. also contributed to the design of the workshop's methods and helped facilitate the workshop. J.P.-G. led the drafting of the Global breakout group section. I.W.B. led the drafting of the Caribbean breakout group case study. A.M. was a co-PI on the grant and helped lead the organization of the workshop. C.B. produced Fig. 1, including the global and regional maps. All other authors, including A.A.-S., M.H., M.M., R.M., B.M., F.A.-G., E.P., N.B., C.A., B.R., and O.L., otherwise equally contributed to the workshop, subsequent drafting, and review of the manuscript. All authors have read and approved the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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