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**Forum**

# Future of coral bleaching research

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## Abstract

Coral bleaching is the largest global threat to coral reef ecosystem persistence this century. Advancing our understanding of coral bleaching and developing solutions to protect corals and the reefs they support are critical. In the present article, we, the US National Science Foundation–funded Coral Bleaching Research Coordination Network, outline future directions for coral bleaching research. Specifically, we address the need for embedded inclusiveness, codevelopment, and capacity building as a foundation for excellence in coral bleaching research and the critical role of coral-bleaching science in shaping policy. We outline a path for research innovation and technology and propose the formation of an international coral bleaching consortium that, in coordination with existing multinational organizations, could be a hub for planning, coordinating, and integrating global-scale coral bleaching research, innovation, and mitigation strategies. This proposed strategy for future coral bleaching research could facilitate a step-function change in how we address the coral bleaching crisis.

**Keywords:** coral bleaching, embedded inclusiveness, coral reef policy, funding, international coral bleaching consortium

Global stressors such as rising temperature and ocean acidification, coupled with local stressors such as pollution and overfishing, threaten the persistence of coral reefs (e.g., Veron et al. 2009, Cantin et al. 2010, Frieler et al. 2012, Chua et al. 2013, Knowlton et al. 2021). In the present article, we focus on the primary cause of large-scale coral bleaching events—heat stress. Thermal stress on coral reefs has increased fivefold since preindustrial times (Lough et al. 2018, Tanaka and van Houtan 2022) with a corresponding increase in the length and severity of marine heat waves that lead to coral bleaching, disease, and subsequent mortality (Eakin et al. 2019, Leggat et al. 2019, Marin et al. 2021). Although ocean acidification is also increasing, its effect on corals in the coming decades is negligible compared with the impact of ocean warming (Krämer et al. 2022, McLachlan et al. 2022, Jury et al. 2024). By some estimates, global coverage of living coral may have already declined by as much as 50% since the 1950s (Eddy et al. 2021), with a loss of 14% in coral cover attributed to climate change over the past decade alone (Souter et al. 2021). By the end of this century, tropical ocean temperatures are expected to rise by another 1–4 degrees Celsius (IPCC 2021). Coral bleaching events are predicted to become more intense and frequent, and coral reefs will almost certainly continue experiencing substantial declines in coral abundance, diversity, and reef growth during this century (e.g., Hoegh-Guldberg et al. 2007, Eakin et al. 2009, Veron et al. 2009,

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Hoegh-Guldberg 2011). Studies show that coral natural adaptation is unlikely to keep pace with the rate of rising temperatures (Logan et al. 2014, Bay et al. 2017, Matz et al. 2018, Matz et al. 2020, Bairos-Novak et al. 2021, Smith et al. 2022). At the current rate of ocean warming, some studies predict the collapse of coral reef ecosystems as early as 2060 (e.g., Kleypas et al. 2021, Lachs et al. 2024), whereas others show the possibility of coral communities changing yet persisting when warming is limited to an increase of 2 degrees Celsius (McLachlan et al. 2022, Price et al. 2023, Jury et al. 2024). Research shows that for coral reefs to persist beyond this century, emissions need to be reduced, and active interventions implemented where possible or necessary (Knowlton et al. 2021, Voolstra et al. 2021) to give space and time for corals to acclimate or adapt (e.g., Torda et al. 2017, Coles et al. 2018, Jury et al. 2019, Matz et al. 2020). Efforts to manage the numerous local stressors that also exert significant impacts on coral reefs (i.e., habitat destruction, coastal development, eutrophication, sedimentation, pollution, and overfishing) are also clearly important (Donovan et al. 2021) but may have little consequence for long-term reef persistence if the threats posed by climate change and local stressors are not addressed (e.g., Pandolfi et al. 2005, Winston et al. 2022).

The state of coral reefs thus hinges on the ability of corals to respond to ocean warming, and time is running out for humans to mitigate that trajectory (Knowlton et al. 2021). Coral researchers, managers, and policymakers have a narrowing window of opportunity to optimize and apply research efforts to affect positive change on coral reefs around the globe (van Oppen et al. 2015, Anthony et al. 2017, van Oppen et al. 2017, Peixoto et al. 2022, Voolstra et al. 2023). One way to increase the efficiency of ongoing research and accelerate the rate of discovery and possible solutions is to develop common and standardized frameworks for experimental design, sample collection and archiving, and for working across biological and physical scales from cellular to global.

Through a series of three workshops, the US National Science Foundation–funded Coral Bleaching Research Coordination Network (USCBRCN) addressed this need and developed common frameworks for experimental studies of coral bleaching (McLachlan et al. 2020, Grottoli et al. 2021), for sample collection and archiving (McLachlan et al. 2021, Vega Thurber et al. 2022), and for working across biological and ecological scales (van Woesik et al. 2022). The adoption of these frameworks by coral bleaching researchers could enhance comparability among studies, maximize the use of collected reef biomaterial (i.e., samples), and increase our ability to develop tools for integrating disparate data streams—paving the way for collaboration, moving coral bleaching research forward faster, and reducing the time to discovery (see the supplemental material for additional details). These frameworks also provide a roadmap for current coral bleaching research practices. Critical next steps in coral bleaching studies that go beyond research and apply findings to real-world solutions can benefit from investments in embedded inclusiveness, codevelopment, capacity building, a willingness to take on large-scale research actions, and the integration of research findings with policy decision-making (figure 1). To develop a synthesis and blueprint for the next steps in coral bleaching research, a fourth workshop was held ahead of the 15th International Coral Reef Symposium 2022. All USCBRCN participants from the first three workshops were invited (see the supplemental material for additional details).

The USCBRCN was formed through the U.S. National Science Foundation Research Coordination Network Program (which is how the name came about). Some participants were directly

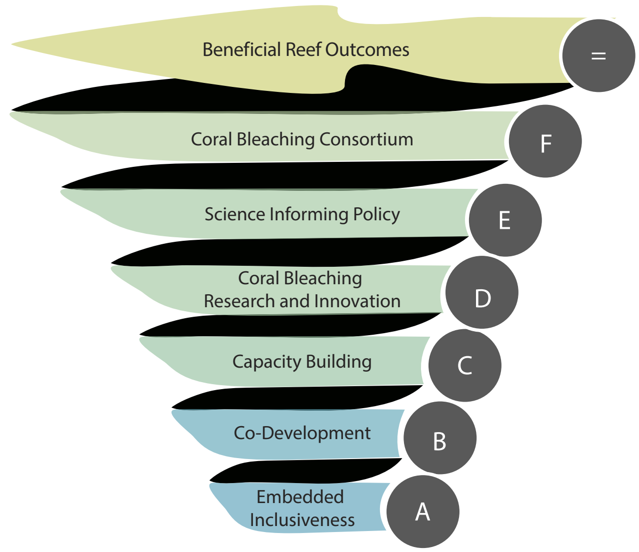


**Figure 1.** Conceptual representation of the future of coral bleaching research. Anchoring the research at conception is (a) embedded inclusiveness and (b) codevelopment where financial support is available to local collaborators and provides the strongest foundation for then (c) building capacity, (d) strengthening research and innovation, and for (e) informing policy. The timing for each step will be project and location dependent. (f) A coral bleaching consortium may be one structural way to guide coral bleaching research globally and lead to beneficial reef outcomes.

invited and some were selected from applications that were openly solicited through the coral reef ecosystem internet discussion forum Coral-list, which has over 9000 members and is managed by the International Coral Reef Society. Care was taken to invite participants from all career stages, with a wide range of expertise (e.g., biology, geology, physical oceanography, modeling) and with near equal gender representation. Because of funding-agency-imposed restrictions, at least 90% of the participants had to be from US institutions for the first workshop. Recognizing the need to increase international representation, the USCBRCN steering committee negotiated with the National Science Foundation to increase the number of international participants to 20%, 20%, and 30% for the second, third, and fourth workshops, respectively. Moving forward, we propose the development of an international coral bleaching consortium made up of researchers, practitioners, social scientists, stakeholders, and local and Indigenous knowledge holders from around the globe, to instigate and promote bold discovery and intervention to enhance the potential for beneficial outcomes for coral reefs (figure 1).

## Directions for the future of coral bleaching research

Sixty-four percent of coral reefs are located within the geographic boundaries of low, low- to middle-, and middle-income countries as defined by the World Bank (Pascal et al. 2016). However, 75% of research on coral reefs is led by investigators from high-income countries, and progress toward equity, diversity, inclusion, and justice has been slow in the coral research community (Ahmadia et al. 2021). When coral reef research efforts are led solely or predominantly by nonlocal individuals, it perpetuates inequality (Trisos et al. 2021) and is logistically inefficient because it ignores Indigenous and local ecological knowledge and expertise. The well-documented practice of parachute science excludes

**Table 1.** Summary of proposed paths forward in coral bleaching research.

| Path | Steps |
|---|---|
| Embedded inclusiveness, codevelopment, and capacity building | Provide direct funding to low- and middle-income country collaborators from high-income countries.<br>Codevelop research programs through open, virtual, and in-person forums that bring people together to include various voices and perspectives, and forms of knowledge.<br>Develop a capacity-building pipeline for coral reef science training at all levels, across disciplines, and among nations. |
| Research shaping policy | Deliver a unified message: Coral reefs are in crisis. Evidence-based solutions that address local to global stressors, coupled with technology and innovation interventions, are critical to coral reef persistence and survival.<br>Communicate science-based solutions for the coral crisis that resonate with policymakers, the public, and representatives in science diplomacy.<br>Participate in the drafting of documents for international policy initiatives that can protect coral reefs. |
| Coral bleaching research, bio- and geoengineering innovation | Explore all aspects of the coral holobiont potential for survival this century through long-duration, multi-stressor studies.<br>Maximize what can be learned from all research through improved metadata and a central database of planned and ongoing projects.<br>Evaluate bioengineering solutions to increase coral resilience including assisted evolution methods (e.g., selective breeding, hybridization, trans-basin transplantation, gene editing), Symbiodiniaceae manipulation, probiotic treatments, increased nutrition through enhanced feeding, and novel technologies to enhance larval recruitment and survivorship.<br>Evaluate geoengineering solutions to reduce solar radiation and seawater temperature. |

local researchers and opportunities for capacity building (Stefanoudis et al. 2021), can produce findings that fail to address region-specific priorities, perpetuates inequities, erodes trust, and misses opportunities for the codevelopment of transformative research (Trisos et al. 2021). In fact, because of restrictions by the funding agency that supported the workshop, the participants and resulting coauthors of this publication were not as inclusive as they could have been.

## Path forward for embedded inclusiveness and co-development

Local researchers, community members, and Indigenous groups have intimate familiarity with their region's respective reefs and are versed in the cultural context within which conservation and research efforts occur (Barber et al. 2014, Winter et al. 2020a, Ainsworth et al. 2021). A genuine, long-term and codevelopment approach between nonlocal and local researchers and practitioners, from conception to implementation, fosters embedded inclusiveness (Royal Society 2011, Barber et al. 2014, Hind et al. 2015, Winter et al. 2020b, Love et al. 2021, Stefanoudis et al. 2021, Trisos et al. 2021). Codevelopment, the collaborative weaving of research and practice (Chambers et al. 2021), increases the potential for incorporating Indigenous and local knowledge into hypothesis development while creating a bridge for the coupling of traditional and scientific approaches (Sterling et al. 2017, Winter et al. 2020b). Traditional ecological knowledge provides unique insights derived from centuries of observation, experimentation, and adaptation within reef ecosystems that are invaluable for sustainable resource management and biodiversity conservation (Sinthumule 2023). Although it has been historically overlooked by Western science, traditional ecological knowledge is increasingly acknowledged and valued by Western scientists (Gómez-Baggethun et al. 2013). It also provides training and equipment acquisition opportunities to underrepresented groups (Hind et al. 2015, Price and Toonen 2017, 'Ohukani'ohi'a III Gon et al. 2021, Ainsworth et al. 2021, Singeo and Ferguson 2023). Finally, codevelopment increases trust within local communities of research outcomes, engages local decision-makers, and promotes cooperative and successful policy actions (Singeo and Ferguson 2023). For example, such codevelopment has been successfully implemented in oyster bed restoration activities (Smith et al. 2022) and has since been proposed as a general strategy for all restoration activities (Crane et al. 2017, Price and Toonen 2017, Forsman et al. 2018, Sweet et al. 2021, Merchant et al. 2022).

However, the current funding structure of many agencies is a barrier to codevelopment. The future of coral bleaching research could build a better culture of embedded inclusiveness and codevelopment if funding agencies in high-income countries required that research conducted in low- and middle-income countries include codeveloped collaborations and coleadership with local partners, as well as direct financial support of those local partners (table 1). Codevelopment is ideally integrated at all levels of the research starting at the inception or proposal stage, through to the in-country research, and ending with the publication and future new collaborations. For this to be most effective, funding agencies would allow for funds in grants to financially compensate and support local collaborators (e.g., individuals at academic institutions, nongovernmental organizations, government agencies, national laboratories, field stations, teaching and learning centers, informal science centers). Collaborative partnerships and strong relationships are developed over time and with sufficient resources. Improving direct access for researchers in developing countries to funding as project leaders or coleaders, supported by agencies in high-income countries, could be a powerful way to facilitate the establishment and maintenance of equal research collaborations. Recently, the Coral Research and Development Accelerator Platform (CORDAP) has implemented a funding model that requires codevelopment, coleadership, and financial support of all partners including those in low or middle-income countries.

Codevelopment of research programs can be facilitated through open, virtual, and in-person forums that bring people together to include various voices, perspectives, and forms of knowledge (table 1). Building trust with local communities will take time to overcome a history of disenfranchisement in the research and policy space (Torres-García et al. 2024). One starting point could include open and accessible webinars and workshops, hosted by a suite of sources (e.g., research coordination networks, organizations such as the International Coral Reef Society or the Coral Restoration Consortium, journal-led monthly events) that could help facilitate multidirectional science communication and research codevelopment (Davies et al. 2023). Another step would include researchers participating in community-led activities, including community workdays, that build reciprocal rather than extractive relationships. Days engaging with communities ideally are in addition to research days while at a study site to build trust between researchers and local communities (Kūlana Noiʻi Working Group 2021). Flexibility by funding agencies to allow for grants to cover the travel and participation costs for individuals from outside of the funding agency's country is critical to ensuring the input of a broad range of voices. Community engagement prior to project development ensures data sovereignty and access agreements are incorporated into proposals (Kūlana Noiʻi Working Group 2021, Ravindran 2024) and increases the potential for incorporating community needs into proposals. One challenge is maintaining relationships and commitments with local communities beyond the traditional 1–4-year grant period. The conducted research may be a short-term outcome for researchers but could represent a longer commitment by local communities (Torres-García et al. 2024). When taken together, these actions and considerations could help create a more equitable, diverse, accessible, inclusive, and just landscape for coral bleaching research. Such a strategy would also foster more creative research, facilitate new discoveries, and strengthen the adoption of evidence-based conservation and management decisions at all levels.

## Capacity-building

Capacity building includes training the next generation of coral researchers, managers, and policymakers around the world. There are currently institutional barriers and funding restrictions that limit capacity building (Davies et al. 2021, Davies et al. 2023). In addition, limited funding in developing countries or political instability that impedes funding can preclude investment in modern research infrastructure in those countries, making it harder to train the next generation of scientists, managers, and practitioners (Barber et al. 2014). The disparity in funding opportunities among low-, middle-, and high-income countries is exacerbated by the cost of journal subscriptions, resulting in publications and their data sets being hidden behind paywalls (Roche et al. 2015, Piwowar et al. 2018). Funding agencies could require that all publications resulting from the work they support be published open access and provide the funds to do so. Access to higher education can be inaccessible because of cost, logistics, and scholarship requirements. Programs such as that by the Coastal Oceans Research and Development—Indian Ocean (CORDIO) initiative (Obura et al. 2012) that are more equitable, diverse, and inclusive (e.g., and have fostered embedded inclusiveness; Barber et al. 2014, Richmond 2014, Love et al. 2021) can serve as models for capacity building to the coral bleaching community.

Jump-starting capacity building can be initiated by developing a pipeline for coral reef science training at all career stages, across disciplines, and among nations (table 1). Individuals from diverse countries (e.g., low, middle, and high income) and career stages (e.g., local community leaders and grass roots organizations, regional students, undergraduate and graduate students, researchers, and practitioners) could be recruited for training, networking, and professional development programs. As a starting point, programs such as the World Bank's capacity-building Graduate Scholarship Program (World Bank 2025) and the United Kingdom Research and Innovation (UKRI) Future Leaders Fellowships program (UKRI 2024) could be extended to include wider participation and serve as models for new programs. The World Bank's program is for applicants from developing countries to receive graduate level training abroad and then return to their home country. The UKRI program funds students from any country to study in the United Kingdom. Both programs provide training opportunities to students from low- and middle-income countries and incentives to return to their country, contributing to local capacity building. Within the United States, an international version of the National Science Foundation's Research Traineeship Program (NSF 2024) could provide additional opportunities for capacity building. It has been suggested that for every graduate student from a high-income country who visits a developing country to do research, there should be funding for a reciprocal visit for a student from the low- or middle-income country to be trained in the high-income country (Trisos et al. 2021). To that end, funding agencies could consider adding reciprocal training as a requirement in grant proposals and could provide criteria and additional funding needed to support these activities.

## Role of research and researchers in shaping policy

Research is the foundation for evidence-based policy decisions. New policy actions for coral reefs that consider solutions for people and the environment are the most effective because of the multitude of benefits a healthy reef provides (Hoegh-Guldberg et al. 2019, Dundas et al. 2020, Knowlton et al. 2021). Moreover, translating scientific findings into policies and actions benefits from fostering a diverse and inclusive research and policymaking arena (see the "Directions for the coral bleaching RCN" section), and effective communication, decision analysis, diplomacy, and incentives (Lee et al. 2019, Polejack 2021). This successful model is exemplified, for instance, by the CORDIO (Obura et al. 2012, von Winterfeldt 2013) initiative—an internationally funded regional network that monitors coral bleaching events in East Africa and across the Indian Ocean and influences government policy by having representatives on high-level intergovernmental panels and boards while also providing capacity development across the region. CORDIO can serve as a model for other organizations and countries for bridging science and policy.

## Path forward for research shaping policy

At individual and organization scales, all researchers can elevate the impact of their coral bleaching research in shaping policy by delivering a clear and unified message about the coral reef crisis and the need for evidence-based solutions, by leveraging creative messaging platforms to effectively communicate science-based solutions for the coral crisis to policymakers and other stakeholders, and by engaging in the writing of international policy initiatives that can protect coral reefs. These three courses of action are interdependent to achieve the goal to safeguard reefs, with urgent and pronounced emissions reduction critical to the effectiveness of all other efforts.

Increasing the impact of research findings for the full spectrum of end users (e.g., policymakers, government, practitioners, the private sector, researchers, educators, the general public) and influencing the adoption of policy solutions to coral bleaching events could benefit from a shared, unified, common message about the coral reef crisis. One suggestion would be a statement that both advocates for greenhouse gas emission reductions and the implementation of evidence-based actions that benefit coral reefs (table 1). Building on the sentiment echoed in our discussions and in many reviews and white papers (e.g., Kleypas et al. 2021, Knowlton et al. 2021, Reimer et al. 2024), we propose a unified statement could be "Coral reefs are in crisis. Evidence-based solutions that address local to global stressors, coupled with technology and innovation interventions, are critical to coral reef persistence and survival." If researchers and practitioners unite around this message and incorporate it into their publications and presentations, it would help to enhance the power of the message. Examples of how actions directly benefit coral reefs (Knowlton et al. 2021, Carlson et al. 2022) and of the cost of inaction (Peixoto et al. 2022) are well documented. Sharing some of the evidence-based findings with stakeholders on the consequences of coral bleaching on human well-being (e.g., childhood stunting due to loss of fish-derived protein; Chaijaroen 2022) and economic stability (Crosby et al. 2002) can also serve as a tool for increasing commitments from national and international bodies to take action to mitigate climate change and implement solutions to protect coral reefs.

Scientific journals remain the primary means of disseminating research to other researchers, but policymakers do not necessarily rely heavily on scientific articles as an information source. Furthermore, high publication and access fees may sometimes represent accessibility barriers to those outside of large research institutions (Cvitanovic et al. 2015). Having a universal practice of a tiered pricing structure for publication costs, as many journals already do, could greatly enhance equitable access for researchers. In addition, journals that allow for publication in languages other than English, such as *Coral Reefs* and many of the American Geophysical Union journals, increase equity and inclusion in research dissemination. Alternative platforms for disseminating research more equitably include local listening sessions, white papers, webinars, public press (e.g., newspapers, magazines), teaching and learning resources, and targeted presentations to specific groups and advisory councils that inform the direction of policy and practice (Mea et al. 2016). Investment in better methods for communicating research findings within journal platforms (Doubleday and Connell 2017, Freeling et al. 2019), as well as outside of the scientific journal platform requires a change in how academic and government institutions recognize and reward nonstandard academic publications in the promotion process (Davies et al. 2021). By leveraging existing messaging platforms and developing creative communication strategies to effectively convey science-based solutions that resonate with policymakers, the general public, and representatives in science diplomacy we could increase the impact of the message at local (e.g., Stony Coral Tissue Loss Disease Response Effort Communications and Outreach Team) and global (e.g., Conference of the Parties, United National Convention on Biological Diversity, United Nations Ocean Conference) levels (table 1). In addition, maintaining open and reciprocal communication among researchers, managers, local communities, and policymakers will help to ensure that consensus findings regarding coral bleaching and mass mortality events are delivered in accessible formats and that ongoing research continues to align with priority needs. Several existing communities of practice have developed effective and inclusive communication frameworks (i.e., the Coral Restoration Consortium, the State of Florida's Stony Coral Tissue Loss Disease Response Effort, and the Center for Ocean Sciences Education Excellence Island Earth initiative used in Wiener et al. 2016). These could serve as springboards for connecting coral bleaching research findings with stakeholders and policymakers. Alternatively, the existing communication frameworks could serve as models for effective messaging for a new coral bleaching consortium (see the conclusion).

Finally, coral reef scientists could remain directly involved in drafting documents for international policy initiatives that can protect coral reefs (e.g., United Nations post-2020 Global Biodiversity Framework, the International Coral Reef Initiative, Committee of the Parties on Climate Change; table 1). Such documents are designed to influence negotiations over global commitments on emissions reductions of greenhouse gasses, protection of natural ecosystems such as coral reefs, and support scientific discovery, capacity building, technology development, and information exchange (Polejack 2021). The governments of coral-rich developing countries will have the greatest influence in ensuring successful mitigation of local stressors whereas high-income nations are likely to have the greatest influence on global carbon emissions. Local researchers in coral-rich nations can uniquely combine disciplinary authority on coral reefs and familiarity with their government and culture to become effective diplomats for informed policy decisions in their countries, as well as internationally. It is also important for well-funded researchers and institutions in developed nations to collaborate with and amplify the voices of their counterparts in coral-rich developing nations as described in the "Embedded inclusiveness, codevelopment, and capacity building" section. A strong and fluid connection among research findings, researchers, local stakeholder needs, and policymakers will ensure that the best policies are developed and implemented at all scales.

## Path forward for coral bleaching research and innovative technological approaches

Moving coral bleaching research in a forward direction requires us to explore the coral holobiont (the coral animal together with its protist, bacteria, viral, and fungal partners) in multistressor situations across spatial and temporal scales. Doing so will lead to a better understanding of the individual roles of each component in health and bleaching and inform the subsequent expansion of research into higher-risk approaches for developing scalable restoration and engineering solutions. The catastrophic rate of coral loss necessitates thoughtful research-informed actions that reflect constantly emerging findings. Success will be optimized when all stakeholders are involved and embedded inclusiveness is part of all aspects of the work. (See the "Embedded inclusiveness, codevelopment, and capacity building" section for details.)

## Pushing our knowledge of coral bleaching further

New research frontiers for understanding coral bleaching will require exploring the adaptive potential of the coral holobiont (i.e., host, endosymbiotic algae, and microbiome) in the context of multiple stressors over time (table 1; e.g., Wiedenmann et al. 2013, Pogoreutz et al. 2017, Donovan et al. 2021, Grottoli et al. 2021, Collins et al. 2022). Coral bleaching is often associated with disease outbreaks, so understanding the relationship among bleaching, disease, and what confers disease resistance and resilience during marine heat waves remains a critical knowledge gap (e.g., Miller et al. 2009, Vega Thurber et al. 2014, Merselis et al. 2018). The combined effects of chronic, acute, and variable heat stress, ocean acidification, light, disease, low food availability, low oxygen, elevated nutrient levels, and pollution are just some of the suboptimal conditions that corals regularly face today (e.g., van Woesik and Randall 2017, Reichert et al. 2021, Dobson et al.

2021a, 2021b, Alderdice et al. 2022, Gómez-Campo et al. 2022). Research on processes operating from the subcellular to the basin scale (van Woesik et al. 2022), over long durations (Grottoli et al. 2021), and in the context of interactions with other reef taxa (e.g., Detmer et al. 2022, Grupstra et al. 2022, Jury et al. 2024) pushes our knowledge of coral bleaching further. Studies addressing these concepts could be explored through the use of mesocosm and *in situ* field experiments (e.g., Bahr et al. 2020, Paiva et al. 2021, McLachlan et al. 2022) coupled with modeling approaches to integrate findings across studies (e.g., Gómez-Campo et al. 2022, Shlesinger and van Woesik 2023). Ideally, experimental temperature regimens would reflect the long-term history of climate and temperature variability derived from measurements (Heron et al. 2016) and coral skeletal records (e.g., Grottoli and Eakin 2007, Lough 2010, Felis 2020) most relevant to the corals in a study. How natural selection acts on all coral partners (e.g., Chakravarti et al. 2017, McManus et al. 2021) and how environment and thermal history can drive phenotypic plasticity and natural selection (e.g., Grottoli et al. 2006, Fine et al. 2013, Brown et al. 2015, Scheufen et al. 2017, Hughes et al. 2019, Barott et al. 2021) will also be informative in exploring what drives negative outcomes from bleaching and coral resilience to marine heat waves. Results can inform our basic understanding of coral holobiont biology and provide insights to improving coral conservation. For example, a deeper understanding of the life history of the coral's endosymbiotic algal partners, the Symbiodiniaceae, which are responsible for a large proportion of natural variation in bleaching response, is still needed (Fuller et al. 2020, Davies et al. 2023). We are also only starting to scratch the surface on the mechanisms and potential for selection, adaptation, and phenotypic plasticity of heat-stress-resistant (i.e., less likely to bleach under heat stress) and -resilient (i.e., more likely to survive heat stress) corals and their associated symbiotic partners (Levin et al. 2017, Putnam et al. 2017, Morikawa and Palumbi 2019, Barott et al. 2021, Figueroa et al. 2021, Howe-Kerr et al. 2023). Determining whether those traits are heritable (Kenkel et al. 2015, Quigley et al. 2017, Jury et al. 2019, Bairos-Novak et al. 2021) and to what degree they will be constrained by physiological trade-offs or genetic correlations will further our basic understanding of coral biology and genetics and could inform future predictions and interventions (Sgrò and Hoffmann 2004, Muller et al. 2018, McManus et al. 2021, Rodrigues and Padilla-Gamiño 2022).

Maximizing what we can learn from research going forward will be greatly enhanced and accelerated by improving the recording and publishing of metadata associated with observations and experiments (Edmunds et al. 2011, Madin et al. 2016, McLachlan et al. 2020, Grottoli et al. 2021, Toczydlowski et al. 2021) in a supported database that is readable and writable (table 1; e.g., the MEDFORD and GeOMe metadatabases; Shpilker et al. 2022, Deck et al. 2017, respectively). Such procedures are now commonplace for next generation sequence data (data deposited at the National Centre for Biotechnology Information) but are still less common for ecological data. Furthermore, any such effective archiving would acknowledge the sovereignty of Indigenous peoples or nations where the data were collected (Riginos et al. 2020, Liggins et al. 2021). Moving toward a practice of publishing that emphasizes collective benefit, authority to control, responsibility and ethics (CARE; Carroll et al. 2020) and findability, accessibility, interoperability, and reusability (FAIR; Wilkinson et al. 2016) coupled with open science principles and transparency in methods will enhance discoverability of new research and increase the potential for adoption of new frameworks. For example, CARE principles could be advanced through a notices and labels system such as Local Contexts (Liggins et al. 2021), which ensures appropriate Indigenous attribution and data sovereignty. Furthermore, a central database for researchers to register projects at the time of conception as well as archived samples from past projects could facilitate the development of interdisciplinary collaborations, streamline project activities to minimize repetition, facilitate coordination of CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) approvals for sample sharing, and speed up the pace of discovery (table 1; Grottoli et al. 2021, Vega Thurber et al. 2022). The National Science Foundation's AccelNet program is an existing registry that could potentially be leveraged to realize this goal.

## Bioengineering and geoengineering solutions

Bold actions going forward could include a range of bioengineering and geoengineering approaches that may be higher risk but may also be promising for some species and locations. Bioengineering technologies that may be viable paths to increase coral population resilience for some species include assisted evolution (e.g., selective breeding, hybridization, transbasin transplantation, gene editing; e.g., Craggs et al. 2020, Randall et al. 2020, Drury et al. 2022, Bay et al. 2023), Symbiodiniaceae and microbiome manipulation (Rosado et al. 2019), enhanced coral feeding (Dobson et al. 2021a, Denis et al. 2024, Grottoli et al. 2025), and structures to enhance larval recruitment and survivorship (table 1; Jessica Reichert, personal communications). High-throughput thermal tolerance phenotyping (e.g., Coral Bleaching Automated Stress System; Evensen et al. 2023) and genotyping systems are emerging for identifying individuals that may be more useful as broodstock for study, breeding, and restoration (e.g., Tyler et al. 2018, Carradec et al. 2020, Chang et al. 2020, Voolstra et al. 2020, Brown and Barott 2022, Meng et al. 2022). However, methods used to identify parent corals for selective breeding do not always reliably identify coral capacity for tolerating long-term heat stress typical of heatwaves in the ocean (Humanes et al. 2024). More controversially, it may be time to consider assisted migration using coral from different regions within a basin or even from different ocean basins (Hoegh-Guldberg et al. 2008). Parts of the Caribbean may already be candidates for assisted migration because of extreme degradation of some sites coupled with the region-wide breakdown of recruitment of native reef-building species (van Woesik et al. 2014, Roff 2020). Reintroduction of native species to historical or Holocene ranges has been done with *Acropora palmata* in Florida (Kuffner et al. 2020, Chapron et al. 2023), giant clams *Tridacna gigas* in the Philippines (Gomez and Mingoa-Licuanan 2006), and sea otters *Enhydra lutris* in California (e.g., Davis et al. 2019), which can serve to jumpstart sexual reproduction for keystone species. Expanding species ranges beyond historical limits in anticipation of further environmental changes can sometimes also be a viable management alternative (e.g., managed relocation of bull trout *Salvelinus confluentus*; Karasov-Olson et al. 2021). Although assisted migration carries potential risks of unintended species introductions (e.g., associated microfauna, microbiome), the potential benefits could outweigh the risks for the most degenerate reefs (e.g., reefs with less than 1% coral cover). Other bioengineering approaches that are in the early phases of development include genetically modifying corals via CRISPR-Cas systems (Cleves et al. 2020), modification of Symbiodiniaceae or their distribution to prospective hosts (Grupstra et al. 2023), enhancement of coral probiotics (Li et al. 2022, Peixoto et al. 2022), nutritional supplementation through enhanced coral feeding (e.g., the Underwater Zooplankton Light Enhancement Array by

Grottoli et al. 2025 Patent Pending Application Numbers US 19/127,361; AU 2023373381; SA 1120252948) and nanotechnology bioprinting (Roger et al. 2023) to enhance larval recruitment, growth, and survivorship *in situ*. Although some of these bioengineering technologies are already showing promise at small scales (e.g., Morikawa and Palumbi 2019, Evensen et al. 2023, Grottoli et al. 2025), continued study and investment could facilitate the eventual implementation of these bioengineering solutions at scales needed to produce climate change resilient coral populations.

Geoengineering technologies are the least explored approaches to mitigating coral bleaching so far (NASEE 2019, Kleypas et al. 2021). This is likely due to the high cost and the difficulty in predicting their efficacy and potential adverse effects. However, these interventions still warrant exploration since they may be a promising avenue for mitigating thermal stress in some cases and a complementary approach in other cases. Geoengineering technologies being explored to manipulate the environment include those designed to reduce solar radiation (e.g., cloud brightening, surface-albedo enhancement, reef shading) and to reduce sea surface temperature (e.g., artificial upwelling, artificial increases in flow; table 1). For example, artificial upwelling could provide temporal thermal refugia (Sawall et al. 2020) and could promote thermal tolerance if pulses of cooler deeper water intrusions create thermal fluctuations that increase the coral's physiological plasticity as found in some natural upwelling systems (Buerger et al. 2015, Wall et al. 2015).

Both bioengineering and geoengineering approaches are still in various stages of research and development, limiting the immediate applicability of these technologies to coral protection and restoration. Nevertheless, continued investment in both engineering and technological interventions could help identify potential solutions. Partnerships between academic and private enterprises can provide mechanisms for funding projects, decrease the time to implementation and commercialization, can enhance the capacity for scaling up and broad distribution, and can help stimulate a circular economy where restoration and conservation are funded through a business model. Examples of funded programs include CORDAP, a program funded by G20 countries aimed at supporting technology innovation to facilitate coral restoration success. Furthermore, large-scale endeavors to build living reefs to protect coastlines from wave damage and that can sustain heat waves are being developed through programs such as DARPA's (the Defense Advanced Research Projects Agency) Reefense program in Hawai'i and Florida. The Australian Reef Restoration and Adaptation Program and the King Abdullah University of Science and Technology Reefscape Restoration Initiative at Shushah Island are other large initiatives that investigate a number of potential geoengineering, bioengineering, and restoration techniques.

Regardless of the bio- or geoengineering approach, there are three keys to success: Define clear project objectives (e.g., Gann et al. 2019), use measurable indicators to determine the degree of success of project objectives (Boström-Einarsson et al. 2020) and to accordingly modify subsequent engineering interventions on the basis of lessons learned (Guest et al. 2018, Elahi et al. 2022, Knapp et al. 2022, Shlesinger and van Woesik 2023), and assess the capacity to scale up, given that the impacts on reefs are anticipated to increase both spatially and in severity (Hughes et al. 2018). For example, increasing the capacity for culturing and mass production of bioengineered coral fragments and recruits for restoration in a warming world and including genetic diversity goals will be necessary for effective scaling up (Shafir et al. 2006, Forsman et al. 2018, Page et al. 2018). The Coral Spawning Lab, in the United Kingdom, is at the forefront of coral reproduction bioengineering having developed and commercialized an *ex situ* coral spawning system with high recruit survivorship and growth. The system is already being scaled up and implemented internationally. That said, the majority of bio- and geoengineering approaches are still in their infancy and have yet to broach issues of scalability, although they are moving in the right direction. Targeting efforts toward engineering interventions with the highest degree of scalability and focusing on reefs with the greatest potential for reproduction across reef regions will be necessary in a resource-limited reality where the need for immediate solutions is urgent. Furthermore, continued development of partnerships with government bodies and Indigenous knowledge holders is needed to better understand the local context for each project and overcome the permitting and legislative hurdles that currently limit the scope of bio- and geoengineering solution implementation.

## Directions for the coral bleaching RCN

The USCBRCN has united 69 diverse coral bleaching researchers (table 2) and, as a community, could leverage and expand this network for initiating, organizing, and coordinating a path forward as outlined in the previous sections. A next step would be to meaningfully broaden the USCBRCN network to form an international coral bleaching consortium that includes individuals from additional underrepresented and underserved groups, more individuals from countries around the globe, individuals with local and Indigenous knowledge, and individuals and organizations with science-to-policy expertise. Through large international cooperation, embedded inclusiveness, and multidisciplinary collaborations, there is the potential to better address the global impacts facing coral reefs. The consortium could engage in strategic planning to unify the community in mission driven, multinational, multiscale, integrative efforts to tackle the next steps in coral research and innovation, spearhead big science initiatives for coral bleaching, and shepherd them through to policy and applications (box 1). Recruitment to the consortium could be achieved through social media and a consortium webpage with open solicitations for nominations by colleagues, institutions, agencies, and governments. To optimize accessibility and participation, meetings could be online, because this dramatically reduces the cost of participation and minimizes travel-related climate impacts. When in-person participation is desirable, the consortium could provide financial support for travel to members to ensure participation was diverse and inclusive. Implementing such a plan would generate increasingly complex, multiscale, and transdisciplinary research and data streams requiring a mechanism to reduce study redundancy and optimize sharing of samples. One approach to managing the data generated globally could be to help create a platform for effectively and quickly sharing findings with all stakeholders. To be most effective, the consortium could be a hub for facilitating the translation of that science into policy and action and for facilitating embedded inclusiveness and capacity building practices.

Precedents for complex, diverse, multinational integrative projects exist in programs such as the Mars Mission and the Large Hadron Collider. Smaller scale examples of multinational integrative coral reef programs include the Tara Pacific (Planes et al. 2019), Reef Check (www.reefcheck.org), and the Mission Iconic Reefs (MIR 2025). These programs demonstrate that large complex integrative initiatives can work and lay a pathway for an international coral bleaching consortium initiative. An international coral bleaching consortium could have as a core mission to coordinate collaborative and inclusive international

**Table 2.** Demographic summary of participants at all Coral Bleaching Research Coordination Network workshops.

| | Workshop 1 | | Workshop 2 | | | Workshop 3 | | | Workshop 4 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Participants | Number | Percentage | Number | NSR | Percentage | Number | NSR | Percentage | Number | NSR | Percentage | Total | Average percentage |
| Total | 27 | 100 | 29 | 3 | 100 | 29 | 2 | 100 | 39 | 31 | 100 | 124 | 100 |
| Women | 14 | 52 | 17 | 2 | 59 | 11 | 0 | 38 | 21 | 16 | 54 | 63 | 51 |
| Men | 13 | 48 | 12 | 1 | 41 | 18 | 2 | 62 | 18 | 15 | 46 | 61 | 49 |
| Non-White | 5 | 19 | 4 | 1 | 14 | 7 | 0 | 24 | 11 | 10 | 28 | 27 | 22 |
| PD+GS | 5 | 19 | 7 | 0 | 24 | 8 | 0 | 28 | 7 | 5 | 18 | 27 | 22 |
| early career | 8 | 30 | 9 | 1 | 31 | 8 | 0 | 28 | 13 | 12 | 33 | 38 | 31 |
| mid-career | 6 | 22 | 5 | 2 | 17 | 8 | 1 | 28 | 11 | 9 | 28 | 30 | 24 |
| senior | 8 | 30 | 8 | 0 | 28 | 5 | 0 | 17 | 8 | 6 | 21 | 29 | 23 |
| United States | 24 | 89 | 24 | 2 | 83 | 23 | 1 | 79 | 26 | 21 | 67 | 97 | 78 |
| International | 3 | 11 | 5 | 1 | 17 | 5 | 1 | 17 | 13 | 10 | 33 | 26 | 21 |

*Note:* Career stages were categorized as early career (assistant professor or equivalent), midcareer (associate professor or equivalent), and senior (full professor or equivalent). Workshop 4 was a synthesis workshop of the previous three, which was designed to be composed almost entirely of previous participants. In total, there were 69 unique participants. To comply with the funding requirements, at least 90%, 80%, 80%, and 70% of the participants had to be from US institutions for the first, second, third, and fourth workshops, respectively. *Abbreviations:* NSR, nonsteering repeat participants; PD+GS, postdoctoral researchers and graduate students.

**Box 1.** Example of a possible coral bleaching consortium initiative.

An international coral bleaching consortium could facilitate the exploration of coral holobiont potential for survival this century (table 1) by coordinating a global, integrated, and multinational project of standardized, long-duration, multistressor experiments to evaluate coral- and regional-specific signatures of heat stress. Such a project would help to identify coral populations that are most thermally tolerant; to elucidate their shared and unique holobiont characteristics at local, regional, and global scales, and to enable the development of large-scale efforts to ground-truth or test hypothesized relationships between traits, environmental drivers, and susceptibility to future mass bleaching events. Coordinated efforts would further facilitate and support the sharing of samples, results, and metadata across researchers (e.g., Grottoli et al. 2021, van Woesik et al. 2022, Vega Thurber et al. 2022), and provide unprecedented insights into fundamental rules governing coral biology and resilience. Furthermore, results from such large-scale studies would inform conservation efforts at local, regional, and global scales, by identifying thermally tolerant populations and species. In addition, bioengineering solutions could be evaluated as possible intervention strategies during and after marine heatwaves, and determining the scale over which management and technology approaches could be shared among regions.

An international coral bleaching consortium could further facilitate the codevelopment of a large-scale project like this with countries around the world to coordinate the experimental designs, facilitate comparisons among experiments and bioengineering interventions, and coordinate large-scale interpretations. This initiative would rely on local workforce codevelopment and Indigenous knowledge to be successful. Then using consistent data collection and protocols, monitor those corals until a mass bleaching occurs and for a long period following the bleaching event. Such a study would facilitate our understanding of the relationship between the environmental characteristics of bleaching events and coral survival following these events on a local to global scale. An international coral bleaching consortium would have the reach and expertise at all levels to put such findings into context and codevelop management and policy strategies to prevent further loss of coral reef habitats.

coral bleaching science and policy, coordinate efforts to identify consensus in the coral bleaching community and build communication networks (see example in box 1). Any new consortium would also need to avoid overlap with current efforts, work collaboratively with existing efforts, and work to bridge the translational gap from discovery to policy and application. A registry for data, metadata, and ongoing projects that could reduce overlap and encourage sharing of samples and international collaborations can persist only if there are long term financial commitments to sustain it. Such a database could also be instrumental in developing metadata characteristics of reef sites around the world. The Coral Restoration Consortium (www.crc.world; Vardi et al. 2021) and the Open Traits Network (https://opentraits.org/; Gallagher et al. 2020) are two examples of existing collaborative communities that have developed effective and inclusive international communication and data frameworks, and these could serve as models for the development of a similar coral bleaching consortium data-sharing platform. Alternatively, new partnerships with existing collaborative networks (e.g., the International Coral Reef Society, the International Coral Reef Initiative, the Coral Restoration Consortium, the Open Traits Network) could be developed to house coral bleaching metadata, project registry data, and sample registry data.

The formation of an international coral bleaching consortium is ambitious and would ideally require investments from multiple funding agencies from multiple countries to support a core of staff to initiate, coordinate, and manage consortium activities, maintain communication with all participants, and manage a project database. The National Science Foundation does have funding to establish centers and could be a starting point for this initiative. CORDAP may also be another avenue for funding. Forming the consortium would be an essential first step to building and supporting the conceptual framework illustrated in figure 1.

## Conclusions

Advancing coral bleaching research and increasing coral reef resilience will require a massive global coordinated effort if we are to make significant progress at a global scale and at a pace that can keep up with or get ahead of climate change and local stressors. An international coral bleaching consortium may be one way to structure such efforts and provide a global umbrella for coordinating innovation in coral bleaching research that leverages truly embedded inclusiveness and capacity building, effectively influences policies, intersects with existing coral research networks and platforms and can increase the chances of sustaining coral reefs at ecologically relevant scales this century (figure 1). Leveraging the cohort of researchers that participated in USCBRCN activities provides only the starting point. The International Coral Reef Society and the International Coral Reef Initiative (who represent a global network of coral reef scientists and practitioners), might serve as logical collaborators for a coral bleaching consortium to broaden the network of participating members and countries and encourage broader action on a global problem. Even without a new consortium, additional collaboration, cooperation, data and project transparency, technological innovation, and embedded inclusiveness are needed to push the global coral bleaching research field and possible solutions and interventions initiatives forward. Embarking on a bolder path to address the coral bleaching crisis will require significant and sustained resources and funding to stimulate the needed research and innovation, to assess the impact of interventions long-term, and to convert evidence-based findings into policies and actions. A comprehensive understanding of coral bleaching and innovation to support resilient coral populations at ecologically relevant scales will require substantial funding and large, inclusive, diverse, multinational, and interdisciplinary teams. Furthermore, existing initiatives (e.g., CORDAP, the Global Coral Reef Monitoring Network, the NSF Directorate for Technology, Innovation, and Partnerships) are independently focused on restoration, surveys, and technology, respectively, but are disconnected and do not have a structure for working toward integrative solutions across programs. Failing to make a step-function change in how we address this crisis, both scientifically and financially, could result in the ultimate cost—the devastating loss of coral reefs before the end of this century. Further investment of resources and collaborative efforts has the potential to prevent or at least slow further loss of coral reefs for future generations.

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## Supplemental material

Supplemental data are available at *BIOSCI* online.

## Author contributions

Andréa G. Grottoli (Conceptualization, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing), Ann Marie Hulver (Conceptualization, Investigation, Methodology, Project administration, Writing - original draft, Writing - review & editing), Rebecca Vega Thurber (Conceptualization, Funding acquisition, Investigation, Methodology, Supervision, Writing - original draft, Writing - review & editing), Robert J. Toonen (Conceptualization, Funding acquisition, Investigation, Methodology, Supervision, Writing - original draft, Writing - review & editing), Emily R. Schmeltzer (Conceptualization, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing), Ilsa B. Kuffner (Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing), Katie L. Barott (Investigation, Methodology, Writing - original draft, Writing - review & editing), Iliana B. Baums (Investigation, Methodology, Writing – original draft, Writing – review & editing), Karl D. Castillo (Investigation, Methodology, Writing - original draft, Writing - review & editing), Leila Chapron (Conceptualization, Investigation, Methodology, Writing - original draft, Writing - review & editing), Marie Alice Coffroth (Investigation, Methodology, Writing - original draft, Writing - review & editing), David J. Combosch (Investigation, Methodology, Writing - original draft, Writing - review & editing), Adrienne M.S. Correa (Investigation, Methodology, Writing – original draft, Writing – review & editing), Eric D. Crandall (Investigation, Methodology, Writing – original draft, Writing – review & editing), Megan Donahue (Investigation, Methodology, Writing - original draft, Writing - review & editing), Jose M. Eirin-Lopez (Investigation, Methodology, Writing - original draft, Writing - review & editing), Thomas Felis (Investigation, Methodology, Writing - original draft, Writing - review & editing), Christine Ferrier-Pagès (Investigation, Methodology, Writing - original draft, Writing - review & editing), Hugo B. Harrison (Investigation, Methodology, Writing – original draft, Writing – review & editing), Scott F. Heron (Investigation, Methodology, Writing – original draft, Writing – review & editing), Danwei Huang (Investigation, Methodology, Writing - original draft, Writing - review & editing), Adriana Humanes (Investigation, Methodology, Writing - original draft, Writing - review & editing), Carly D. Kenkel (Investigation, Methodology, Writing - original draft, Writing - review & editing), Thomas Krueger (Investigation, Methodology, Writing - original draft, Writing - review & editing), Joshua Madin (Investigation, Methodology, Writing - original draft, Writing - review & editing), Mikhail V. Matz (Investigation, Methodology, Writing – original draft, Writing – review & editing), Lisa C. McManus (Investigation, Methodology, Writing – original draft, Writing – review & editing), Monica Medina (Investigation, Methodology, Writing - original draft, Writing - review & editing), Erinn M. Muller (Investigation, Methodology, Writing - original draft, Writing - review & editing), Jacqueline L. Padilla-Gamiño (Investigation, Methodology, Writing - original draft, Writing - review & editing), Hollie M. Putnam (Investigation, Methodology, Writing – original draft, Writing – review & editing), Yvonne Sawall (Investigation, Methodology, Writing - original draft, Writing - review & editing), Tom Shlesinger (Investigation, Methodology, Writing - original draft, Writing - review & editing), Michael J. Sweet (Investigation, Methodology, Writing - original draft, Writing - review & editing), Christian R. Voolstra (Investigation, Methodology, Writing – original draft, Writing – review & editing), Vriginia M. Weis (Investigation, Methodology, Writing – original draft, Writing – review & editing), Christian Wild (Investigation, Methodology, Writing - original draft, Writing

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## Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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