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PERSPECTIVE OPEN

Integrating equity-focused planning into coral bleaching management

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Coral bleaching, associated with warm water temperatures of the oceans, represents the most significant threat to coral reef ecosystems and coastal communities regarding climate change. Coral bleaching prediction models have emerged as essential tools in conservation and policy-making. However, the effectiveness of these models as an equity-focused science-policy nexus remains uncertain when local human community perspectives are disregarded. This paper presents an equity-focused framework for coral bleaching prediction and response, integrating local goals and contexts. We discuss the equity gaps during coral bleaching assessments while emphasizing the importance of early warning systems in promoting and facilitating more accurate reporting of bleaching episodes. Additionally, this research also highlights the complex but inherent interactions of multiple drivers, underscoring the need for cautious and socially inclusive strategies for climate adaptation. This perspective paper advocates for an equitable approach in science-policy networks to support the preservation of coral reefs while safeguarding the well-being of reef-related coastal communities.

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CORAL BLEACHING AS A MODEL FOR A SCIENCE-POLICY NEXUS

Coral bleaching linked to warming oceans is a significant threat to coral reef ecosystems and to coastal communities that depend on reefs for livelihoods, food, medicine, physical protection, and inspirational and cultural values[1]. Since the 1980s, the frequency and intensity of heat stress events causing coral bleaching — defined as the breakdown of the symbiosis between coral hosts and microalgae occurring at a large-scale— have increased, affecting old and new bleaching areas[2,3]. Consequently, there are more calls for adaptation strategies that include temporary or permanent area closures and other restrictions that might support long-term health of coral reefs and their benefits but that can also have current negative impacts on local communities[4,5].

In this context, bleaching prediction models play a crucial role in coral reef conservation by providing information on (i) early warnings, (ii) the current conditions that determine the likelihood of bleaching, (iii) areas with higher risk of bleaching, and (iv) allowing for an opportune response and implementation of appropriate measures to minimize the impacts of bleaching[6,7]. This information already plays an important role within a science-policy implementation loop that informs high-level reef conservation policy[8], supports reef managers to prioritize conservation efforts and resources[7], enables timely adaptive management and monitoring of temporary area closures and fishing quota reductions[9,10] in light of complex interactions between multiple environmental variables[11,12]. Despite the numerous advantages of coral bleaching prediction models and their explicit linkages to management, it is still unclear if the consequent responses are effective as an equitable science-policy tool when they do not consider the needs of local human communities. Failing to include the perspectives and priorities of local communities increases the risk of exacerbating inequalities and leaving vulnerable populations without adequate support and resources in the face of future coral bleaching events.

Here, we refer to social equity as both a goal and a process for ensuring that stakeholders, including communities, governments, and organizations, have equal access to resources, voice, representation in decision-making processes, and the benefits of conservation efforts[13]. This involves transformations for the future through paying particular attention on addressing historical disparities and protecting vulnerable, marginalized, and under-represented groups[14–16]. Normative principles of equity provide a moral and ethical foundation for addressing equity issues, while instrumental (empirical) principles aim to understand and measure the actual impact of actions and policies on fairness and justice so that related objectives can also be achieved[17].

In this perspective paper, we propose an equity-focused framework for guiding coral reef bleaching management based on environmental justice, a widely used concept in conservation literature that combines normative and empirical principles to define equity as a multidimensional concept[17,18]. This enables us to assess how equity dimensions—including distributive, procedural, or recognitional[19–21] —are affected at different scales (e.g., local, regional, or global). In this context, within coral bleaching management frameworks, recognitional equity aims for the voices and needs of reef-related communities to be recognized and valued[19]. Procedural equity refers to decision-making processes that are open, inclusive, and participatory, promoting a sense of fairness and legitimacy in how decisions are made[21,22]. Finally, distributional equity seeks an equitable and just distribution of resources (including their optimization), burdens, and outcomes from ocean use and management[14,15].

To further ground our examples, we focus on various broad steps in coral bleaching management that reflect proposed ideal processes for science-based management of other ocean issues. These include, (i) Implementing an effective early warning system,

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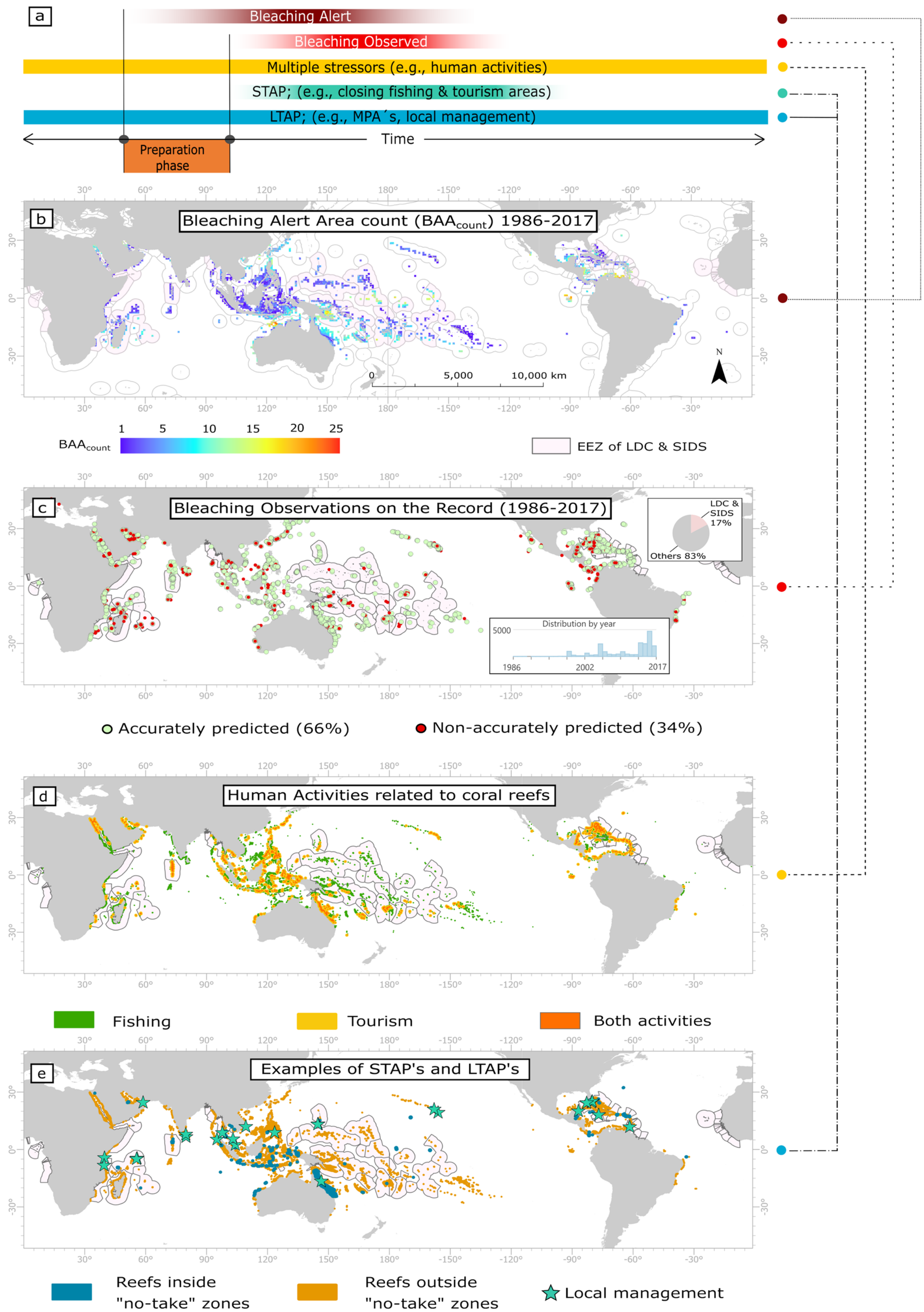


founded on widely accessible products (e.g., satellite-derived data), (ii) building the capacity for a prompt coral bleaching assessment, (iii) identifying and addressing the potential effects of multiple stressors (e.g., other stressors derived from human activities such as fisheries and tourism), (iv) designing and implementing protective response actions and policies with a strong focus on equity, considering social-ecological aspects (Figs. 1a and 2). In each of the sections bellow, we (1) highlight challenges and information gaps that risk inequitable outcomes when moving from coral bleaching alerts to management actions;

Fig. 1 Examples of bleaching-related events and overlapping actions. a Timeline and sequence of the bleaching-related events and overlapping actions. The vertical lines indicate the onset of each "event". Short-term action plan (STAP) e.g., closing major scuba diving and fishing areas. Long-term action plan (LTAP) e.g., marine protected areas (MPA´s) or local management. **b** Map showing the global distribution of the maximum Bleaching Alert Area count (BAA_{count}). It shows how many times coral reefs have been potentially exposed to thermal stress conditions where, at least, the bleaching alert level 1, has been recorded over the period 1986–2017. The data was retrieved from Coral Reef Watch program[24]. **c** Global distribution of the reports of bleaching ($n = 35{,}779$) for the period 1986–2017[3], including the bleaching distribution by year, and among countries group criteria (SIDS & LDC), and accuracy of BAA using a random forest classifier model (see methods supplementary material for details). **d** Example of human activities related to livelihoods and well-being identified as top human stressors[33], and therefore as "multiple stressors". **e** Example of STAP´s ("local management; temporary closures and control of predators")[41] and LTAP´s ("No-take zones") related to coral reefs. Coral reefs polygon's boundaries and local management activities are amplified to facilitate their visualization.

(2) identify key equity dimensions at each step; and (3) suggest pathways for promoting equity in coral bleaching management. Given the very advanced state of knowledge on coral bleaching and its prediction compared to other ocean systems and sectors, lessons learned from this equity-focused approach – from science to local perspectives to actions – can help guide and frame the development of other systems as their knowledge, data, and models evolve.

EQUITY GAPS IN CORAL BLEACHING ASSESSMENT

Early warnings

Effective monitoring of reefs' environmental conditions is a vital component in the early detection of threats for implementing rapid responses, and for building long-term resilience to better protect these ecosystems from further degradation[6,23]. A good example is the most advanced and widely used tool developed by the NOAA's Coral Reef Watch[24] program, the "Bleaching Alert Area" (BAA); a satellite-derived product that can remotely monitor reef conditions and could help predicting bleaching events and disease outbreaks[23], even in regions where ongoing monitoring of environmental conditions is not feasible [Fig. 1b – Bleaching Alert Area count].

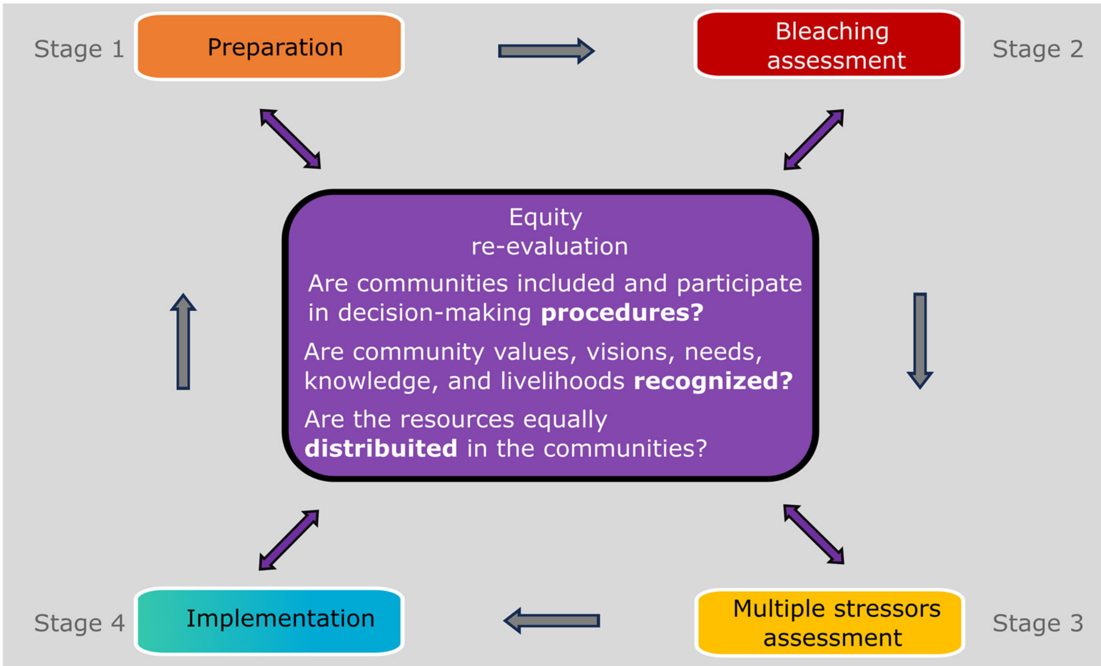
These freely available early warning tools are close to an ideal model envisioned under the UN Decade for Ocean Science (the "Ocean Decade"), where science can quickly and publicly provide information for ocean policy and planning. Nevertheless, it is crucial to recognize that the development of scientific knowledge does not automatically translate into effective and equitable policies[25]. For example, remote sensing algorithms are often validated in areas with higher monitoring capacity but then applied in other areas that might not follow the same pattern, increasing the risk of gathering an "inaccurate" representation; these uncertainties often aren't communicated to end-users, who will ultimately face any risks of using these data in decision-making processes[26,27].

To illustrate this equity risk, we calculated the accuracy (see supplementary material) of BAAs using the maximum monthly value of the bleaching alerts area product[24], and the most comprehensive database of coral bleaching observations[3]. From 1986 to 2017, 66% of bleaching alerts were accurately predicted, while the remaining 34% resulted in either false positives or false negatives (Fig. 1c – Bleaching Observations on the Record). Results in terms of predictive power could of course be further examined by considering factors such as additional environmental drivers, and in-situ sampling efforts (which we discuss in the next section). However, our aim here is to emphasize the potential risks of exacerbating inequalities among resource users when model predictions are the main source of information for decision-making. Specifically, for example, a false positive (i.e., an alert due to thermal stress that does not result in bleaching) could trigger fisheries or tourism area closures, directly affecting local communities and reducing their trust in future science-based decisions. On the other hand, if an alert is not triggered when corals are facing thermal stress (a false negative), it could mislead or lessen the urgency of decisions to take any sort of action. These issues are even more complicated given the uncertainty surrounding the extent to which coral stress mitigation actions truly contribute to reducing bleaching in the future. More importantly, it's worth emphasizing that the implications of these mispredictions become significantly more critical if we consider their inevitable impact on Less Developed Countries (LDCs) and Small Island Developing States (SIDS). As elaborated in section 3.2, these countries often face resource constraints and limited adaptive capacities, increasing, thus, their vulnerability to the adverse effects of false alerts or missed warnings. Therefore, a vital step in reducing inequalities in the context of bleaching prediction models implies ensuring the equitable distribution of accurate information and providing robust decision-making support in these countries.

Coral bleaching reports

Accurately reporting episodes of coral bleaching is essential to assess reef health and validate bleaching prediction frameworks and models[28]. However, differences in monitoring and assessment capabilities of coral bleaching between countries can result in biases in the distribution and frequency of coral bleaching reports and reveal several inequities. For example, reports are primarily in developed nations with more resources and infrastructure to monitor and document such events[23]. Approximately 83% of in-situ bleaching reports are in high- and medium-income countries, with only 17% of reports in developing countries such as Small Island Developing States (SIDS) and Least Developed Countries (LDCs) [Refer to the top right insert in Fig. 1c – Bleaching Observations on the Record. Notice that this insert is located within the map and features a graph]. Additionally, SIDS and LDCs, may also encounter substantial difficulties in accurately reporting and addressing episodes of coral bleaching due to funding and institutional capacity constraints[29]. Finally, monitoring and assessing coral bleaching often require coordination and data sharing among multiple stakeholders, including government agencies, research institutions, and conservation organizations;[30] this coordination capacity is a common constraint in developing regions.

Given that prediction models are primarily both developed and validated in more developed regions, potential errors or biases are, simultaneously, more likely to happen and less known in developing regions. Additionally, potential solutions to mitigate coral bleaching that are also considered in developed-nation contexts may not be adequate for developing regions. As a case in point, a strategy could involve dynamic fishing area closures to respond to bleaching alerts, with some form of compensation program for affected fishers to encourage compliance. This may work in a range of ecological contexts, but also implicitly assumes, among other things, that areas are well mapped, fisher numbers are known, fishers can travel across different areas, and can wait to receive compensation (and that this exists). A lack of these capacities opens up important equity concerns if only some fishers (or tour guides, etc.) would be able to comply and be compensated for losses.



STAGE	DESCRIPTION	Equity re-evaluation
Preparation	Time to anticipate and respond to bleaching	**Procedure** Are early warnings open and accessible to promote involvement of the communities to anticipate and respond to these warnings in a way that they deem appropriate?
Bleaching assessment	Bleaching assessment on intensity and extension	**Distribution** Do the available resources and support for addressing coral bleaching, such as funding and technology, reach communities in need across different geographic areas?
Multiple stressors assessment	Identify potential effects of multiple stressors, e.g., human pressures	**Distribution** Will the way of mitigation of other pressures lead to unequal distribution of benefits and harms among reef-related communities?
Implementation	Short and long-term action plan (STAP & LTAP); at global, national, regional, local scale	**Procedure** How inclusive and participatory is the decision-making on equity during the implementation of these strategies? **Recognition** How are the voices, traditional knowledge, and livelihoods of related communities acknowledged and integrated into policies and practices?

Fig. 2 Planning process description for coral bleaching responses actions and example of guiding questions (based on Crosman et al.[13]) during the "equity re-evaluation" step that considers socio-ecological perspectives. Top panel has been adapted from Pascual et al.[51] and Schreckenberg et al.[17].

Multiple drivers, multiple inequities?

While unusually high seawater temperatures are widely recognized as the primary driver[2], coral bleaching results from the interactions of multiple environmental factors (e.g., light, turbidity, salinity) and anthropogenic pressures (e.g., overfishing, pollution, invasive species)[31]. Since the combined impact of multiple stressors produce complex interactions such as synergies (when the cumulative effects of multiple stressors are greater than the sum of effects produced by the stressors independently) or antagonisms (when the cumulative effect is less than the additive effect)[32], the need to perform preventive measures more "cautiously" to mitigate their interactive effects is advised, though this can come with trade-offs when decisions are made with incomplete understanding of the ecological and social dynamics at play. Take, for instance, the spatial overlap of tourism and fishing, both of which exert significant pressures on coral reefs[33] [Fig. 1d – Human Activities related to coral reefs]. This overlap reveals areas where these activities potentially co-occur with thermal stress presenting opportunities for managing and mitigating their combined impacts on coral health. However, due to uncertainties regarding the heterogeneous responses of corals to rising ocean temperatures[34,35] and the intrinsic interactions with other pressures, the application of interventions or actions to address these challenges could have adverse repercussions. Examples of these repercussions include disputes related to resource allocation (e.g., in the fisheries sector) or economic inequalities in activities (e.g., tourism sector) among individuals and communities. Therefore, understanding these social effects of coral conservation actions can help in preserving coral reefs while minimizing unintended negative consequences.

Implementation of strategies

The successful management of coral reef ecosystems by implementing different strategies has become crucial for dependent coastal communities to protect the biodiversity, promote sustainable use, help build the resilience and facilitate adaptation of coral reefs[36]. For instance, certain reef areas have been temporarily closed or restricted to recreational activities such as swimming, snorkeling, or scuba diving during periods of heat stress in countries such as Malaysia[37], Mexico[38], Thailand[39], and Vietnam[40]. In other places, coral predators (including crown-of-thorns starfish, *Acanthaster* spp., or corallivorous snails, *Duprella* spp, and *Corallophilia* spp.) are constantly monitored and removed to ameliorate the stress on corals when sea temperature is anomalously high[41].

Implementing short-term strategies and action plans (STAP) to mitigate coral stress and alleviate bleaching effects, even if temporary, can present direct challenges to local communities that rely on the activities causing stress[42]. This is of particular concern given the uncertainty surrounding the effectiveness of these strategies in ameliorating bleaching effects, as we may not have sufficient evidence to support the idea that reducing human pressures will lead to the desired ecological outcomes. In essence, the potential benefit of coral protection may not offset the harms of reducing pressures derived from human activities. Moreover, historical injustices resulting from policy gaps in the application of these strategies can also contribute to unequal outcomes, especially when significant social and economic differences exist within these communities[43,44]. For instance, without consideration of people's motivations, benefits, skills, and capacities, poor policy implementation can exacerbate negative consequences for reefs and communities in the short- and long-term[45], particularly in Small Island Developing States (SIDS) and Least Developed Countries (LDCs) heavily reliant on ocean resources for food and economic growth[29].

To exemplify the latter, consider the example of the Solomon Islands, where coral reef fisheries and product extraction are key components of the local economy[46]. Inadequate response capacities, such as regulation and policy implementation regarding extractive coral activities, could create a negative feedback loop. Consequently, this loop could manifest as reduced reef resilience, declining fisheries viability, and compromised livelihoods for reef-dependent communities. This scenario would further exacerbate existing inequalities and, ultimately, lead to the collapse of reef biodiversity, as mentioned by Barlow et al. [47]

Likewise, long-term strategies and action plans (LTAP), although positive, might promote inequalities due to the deeper changes and transboundary implications that their large-scale nature entails. For example, even though recent studies suggest that the creation of large areas of protected reefs (from hundreds to thousands of kilometers) would represent the best opportunity corals have to withstand climate change[7,48], these large marine protected areas (MPAs) [Fig. 1e – Examples of STAP's and LTAPS's] could become barriers to collaboration and worsen inequities among developed and developing countries (and particularly SIDS and coastal LDCs) not only because larger offshore areas require extensive monitoring, surveillance, and enforcement efforts at higher costs[49] but more importantly by neglecting or ignoring local peoples' perspectives[50]. Additionally, when the effectiveness of short-term strategies and action plans (STAP) in mitigating bleaching effects is uncertain, it can lead to unequal outcomes. For example, local communities may invest time, effort, and resources in implementing STAP without a clear understanding of whether these measures will actually protect coral reefs. If these strategies are not to effective, economic losses could occur within the communities with no ecological benefits and a loss of trust in the process itself.

AN EQUITY-FOCUSED APPROACH TO CLIMATE ADAPTATION

A throughline in the examples above is that an equity-focused approach holds that achieving legitimacy among stakeholders through clear and inclusive decision-making processes is essential to not only build trust in management strategies (such as closures or bans), but also plays a crucial role in promoting their effectiveness[51]. Data-driven decision-making, community involvement and engagement, and clear communication are therefore crucial as part of initial steps to achieve effectiveness but also throughout the process and any subsequent monitoring and adaptive management changes[52]. To illustrate this point, research carried out in the Great Barrier Reef Marine Park, Australia revealed that higher legitimacy is perceived by tourism operators than commercial fishers, highlighting the importance of tailoring engagement strategies to different groups within the community[22]. Additionally, this approach, within the framework, must then establish context-dependent thresholds, ensure flexibility, and include robust monitoring and assessment during the second and third phases of coral bleaching management, while continuously adapting and refining management strategies in the subsequent stages (Fig. 2).

Similarly, drawing inspiration from a similar approach in protected area governance and management[17], our framework aims to emphasize the importance of recognizing diverse perspectives, involving stakeholders in decision-making processes, and ensuring the fair distribution of resources to better understand the levels of harm and benefits (see Fig. 2). This emphasis becomes particularly vital when considering strategies such as the creation of large protected reef areas, as discussed in Section 3.4. In cases where such endeavours lack a comprehensive perspective aligned with an equity-focused approach, our framework would prove valuable.

A successful framework also requires dedicated efforts to support institutional governance, finance, monitoring, organizational alignment, collaboration, and dynamic evaluation, allowing impacted communities to redesign and improve adaptation efforts[29]. For example, in states like Tuvalu, which heavily relies on its ocean resources as both a source of food, and a driver of economic growth[53], opinions and perspectives of key stakeholders revealed strong support among locals, government authorities, and the tourism industry for the development of a low-impact tourism destination (Fig. 2). This not only aligns with ecological goals but also promotes equity within reef-related communities.

In summary, while mitigating bleaching is essential within this framework, it's equally crucial to avoid creating or exacerbating social issues that may arise from implementing strategies in the short-term (STAP's) such as bans and area closures, or creating large protected reef areas in the long-term (LTAP's).

LIMITATIONS OF THE FRAMEWORK

Our framework intends to bridge the gap between social and ecological science perspectives, making it relevant to distinct types of stakeholders, including local communities so they may consider how decisions may disproportionately impact them, as well as reef managers, scientists, academia, policymakers, industries such as tourism and fishing, and environmental NGOs, so they can consider how their interventions may proactively avoid negatively impacting local communities[16]. Given the diverse range of stakeholders (and reef-related users) involved, the equity-focused framework for coral bleaching management, while valuable, may also have certain limitations to consider. Some limitations of this approach include the potential resource intensity required for effective implementation, such as financial support. Additionally, the context dependency of each step, actions, and responses may pose significant challenges for different communities. What works well in one community may not be suitable for another, requiring a tailored (and probably costly) solution in each case to account for these differences. This is especially true depending on the scale to which this approach is focused (either local, regional, or global). For example, addressing data gaps, especially in data-scarce regions, is crucial for the effective implementation of the framework. However, filling these gaps could represent significant economic efforts.

In terms of future evaluation of the framework, a potential limitation arises when defining and establishing suitable indicators and metrics for measuring the success and equity of the framework[14,18]. The later would then derive in a complex decision-making if the diverse needs and perspectives of stakeholders in the (decision-making) process lack a consensus, leading to potential conflicts or differences that could exacerbate existing inequities. Finally, from the political and institutional perspective, some institutions may be resistant to change, slowing the implementation and success of the framework.

FUTURE PATHWAYS

To address the structural lack of equity that affect local communities worldwide, it is necessary to go beyond scientific understanding and actively reshape the governance of ocean science[25]. This means ensuring that local and regional institutions in developing countries have equal leadership roles in the formulation and implementation of strategies for sustainable development on coral reefs.

One key aspect is the need for balanced research efforts and outcomes, with a focus on decolonizing the leadership and decision-making processes[54]. As an example of this imbalance, there seems to be a significant disparity in the distribution of current leadership in projects related to coral reefs within the UN Ocean Decade. While ten coral reef-related projects are endorsed (as of May 2023), only a few (three) local or regional institutions in developing countries have a leading role, with most leadership positions held by entities from developed countries (Table S1). This raises important questions about the level of involvement and decision-making power that developing countries have in programs that utilize coral science for conservation, restoration, and associated economies. Thus, it is crucial to assess whether the decisions made in these programs truly align with the best interests and priorities of local communities, promote the centralization of equity, and further the decolonization of coral reef science, conservation efforts, and ocean governance[54].

By dismantling these structural inequalities and granting equal leadership roles to local and regional institutions, the research and conservation efforts can be better aligned to the needs and aspirations of the communities directly impacted by coral reefs. This approach acknowledges the expertize, local and traditional knowledge, and perspectives of local stakeholders and ensures that decision-making processes are inclusive and participatory.

Furthermore, an equity-focused approach should employ accessible and reliable tools for evaluating complex ecosystems such as coral reefs[23]. This includes developing comprehensive and dynamic frameworks that incorporate social, economic, and ecological dimensions (Fig. 2). By understanding and considering the diverse and intrinsically related factors at play, strategies can be formulated to facilitate sustainable and equitable solutions. Such solutions must address not only the preservation of coral reefs but also the well-being and resilience of the communities that depend on them.

Thus, implementing this future pathway of research demands collaboration, resource allocation, mutual learning, shared decision-making, and partnerships that prioritize equitable inclusion, and not only participation. By promoting inclusive governance structures and fostering local leadership, it will become possible to drive toward a positive change, ensure the long-term viability of coral reefs, and contribute to the well-being of the communities directly and indirectly connected to these ecosystems.

DATA AVAILABILITY

The datasets used to generate Fig. 1 were retrieved from previous research that has been referenced in through the text. The links are also available in the [https://github.com/pgonzaleze/BAA_codes] repository.

CODE AVAILABILITY

The code and data regarding the random forest classifier model used in Fig. 1b can be find here [https://github.com/pgonzaleze/BAA_codes].

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COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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