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OPINION

Research priorities to support coral reefs during rapid climate change

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Tropical shallow-water coral reefs, the most biodiverse of all marine habitats, are globally threatened by climate change and the cumulative impacts of other human stressors (Fig 1). A ~1.5˚C warming above pre-industrial levels will induce near-annual coral bleaching and mortality from ~2040 onwards [1], with 2.7˚C warming by 2100 ultimately predicted by the presently most likely scenarios–within the span of a few human and coral generations [2]. Trying to conserve as many coral reefs as possible throughout this century is a global obligation, for two sets of values that are tightly interlinked. First, the protection of the intrinsic values of coral reefs is an ethical responsibility for its own sake [3] and is enshrined through global treaties such as the Convention on Biological Diversity. Second, coral reefs annually provide US $375 billion in monetary and non-monetary values to hundreds of millions of people [1]. They contribute to coastal protection, employment and income from tourism, fishing, and aquarium trade, as well as protein, cultural, spiritual, and recreational values [4]. International agreements such as the Kunming-Montreal Global Biodiversity Framework set targets for the prevention and reversal of losses in the extent, ecological functions, habitat quality and biodiversity of ecosystems. However, for coral reefs, these targets will become unreachable under climate change unless radically new solutions and the willingness to implement known solutions are found [5].

Here we identify three guiding principles to prioritise research and innovation towards the protection of reefs and dependent livelihoods. First, open collaboration is needed to adequately represent the research needs of the approximately 100 low- and lower-middle income nations that are stewards of the most biodiverse coral reefs on Earth. Substantial discrepancy exists between their national research priorities and much of the research conducted predominantly by high-income nations [6]. Data, information and knowledge need to be co-generated and exchanged freely to develop and apply regional solutions [7]. Second, coral reef protection must focus on developing solutions that are scalable, self-sustaining, and at costs that are commensurate with available financing (also considering the cost of lost ecosystem services by not acting) [8]. Third, while the research themes proposed below are set for the coming two decades, these identified solutions will need to be adapted over time, and research must also commence now to start preparing for the vastly uncertain future beyond 2050. Immediately filling critical knowledge gaps is essential since ecological adaptation and implementation of scalable management interventions will take decades, and increasing temperature stress will

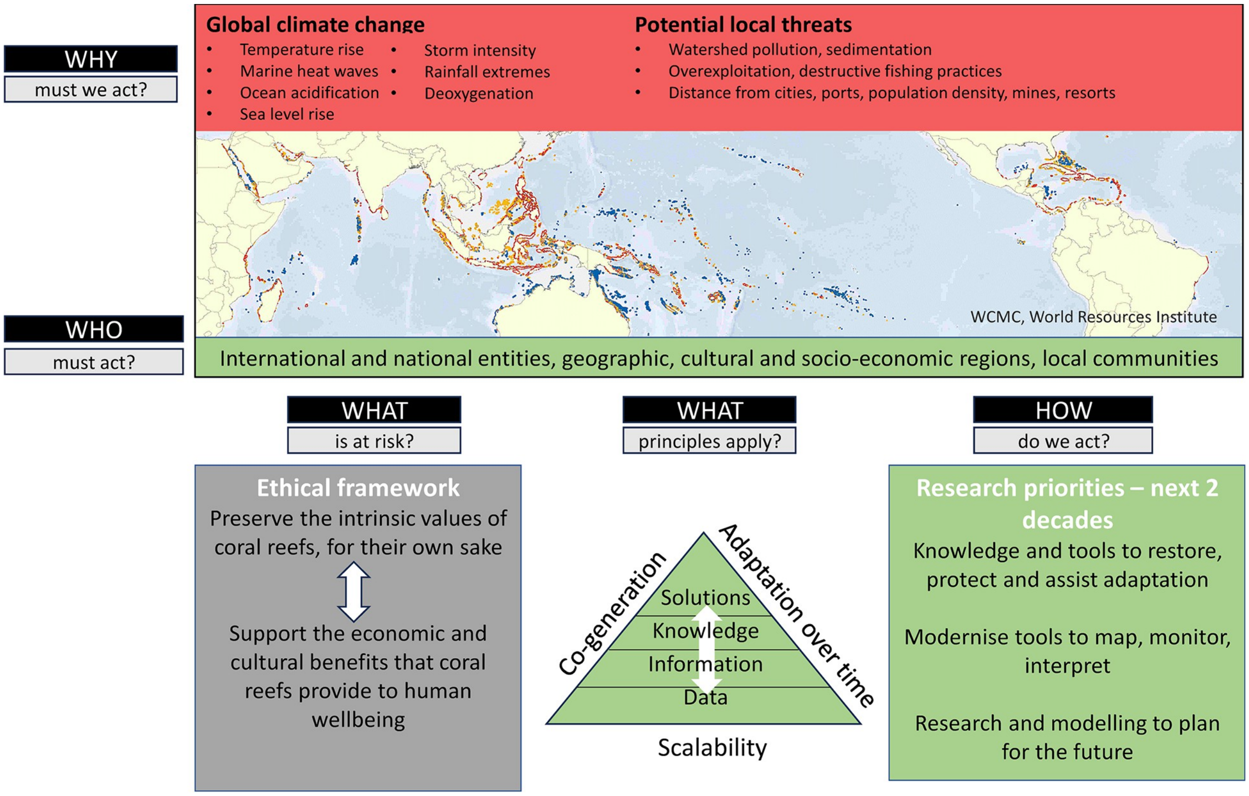

Fig 1. Research priorities underpinning coral reef conservation and management for the next two decades. Solutions will need to be co-developed with environmental managers and policy makers as climate change reaches critical levels for ecosystem integrity and human well-being. Map: Global distribution of warm-water coral reefs, colours represent potential local threats (red: high, orange: medium, blue: low; the threat from global climate change affects nearly all reefs). The map is republished from https://www.wri.org/data/coral-reefs-world-classified-potential-threat-human-activities under a CC BY license, with permission from the World Resources Institute, original copyright 2008.

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undoubtedly be compounded by increasing ocean acidification, sea level rise, and human footprint.

Based on these principles, the greatest research priorities for the coming two decades and beyond group loosely into three inter-related themes. The topics highlighted under these themes are merely indicative of the significant global investment that is urgently required across social science, ecology, genetics, oceanography, economy, modelling, engineering and technology, to support effective conservation decisions by management and policy makers.

- **Develop knowledge and tools to protect and restore:** Effective management of reef fisheries and pollution together with improved governance will remain among the best established tools to accelerate recovery after disturbances [2]. However, the global decline in coral cover shows that they are insufficient on their own in the face of climate change and the expanding human footprint, especially when inadequately resourced [9]. Improving effectiveness, adoption and compliance of integrated management and conservation initiatives also requires new approaches that have not yet been adequately assessed by Western structures [10]. Due to the complexity of coral reefs and of the coral holobiont, and the short window of opportunity remaining, significant research investment is needed to develop ecologically effective and regionally affordable solutions, in order to protect genetic and species biodiversity and to assist ecological and evolutionary adaptation at scale. A range of novel active interventions are now being investigated, including propagating dwindling keystone populations, minimising reproductive losses, adding structural complexity, removing seaweed, assisting gene flow through translocations, selective breeding, and manipulating coral symbioses with more heat tolerant algal endosymbionts [5]. Intervention decisions must be based on ecological knowledge, regional conservation objectives, and benefits-risks assessment including the risks of not acting [5]. As climate change progresses, objectives may have to be lowered towards the maintenance of basic reef functions, including core biodiversity, coastal protection, fisheries and tourism [2].

- **Innovate tools to map, monitor and interpret:** Mapping and monitoring data are needed to rank threats, identify potential solutions and track their effectiveness (Fig 1). Many shallow-water coral reefs have not yet been surveyed to establish their communities, let alone monitored for changes in their conditions. Additionally, potentially 10,000s of km^2 of mesophotic reefs are still uncharted. Recent technological advances have substantially upscaled some monitoring capabilities (remote/proximal sensing, optical, acoustic, eDNA). New AI tools assist in the generation of more standardised, accessible, interoperable and reusable data [11]. Free easy-to-use mapping, monitoring and interpretation tools, local ground-truthing, capacity building and training modules must be developed in collaboration with users across cultural, socio-economic and biogeographic regions to identify region-specific status and threats [12], to monitor the effectiveness of protection measures [2], and to identify regional long-term persistent climate refugia for increased protection [13].
- **Accessible research and modelling for planning reef futures:** Most of the 1 to 9 million reef-associated species are not yet described. Knowledge is sparse even about key ecologically and economically valued taxa, their ecological roles, demography, and adaptation potential to climate change [14]. Foundational research on biodiversity, ecological functions and adaptation remain critical to underpin active reef protection and sustain dependent communities into the future [15]. Built-for-purpose coupled climate-ecosystem-social models must become openly accessible and regionally validated [5] to support environmental management including prioritisation of interventions. Collaborative networks dedicated to training, information sharing, and co-interpretation of data and knowledge across nations with contrasting socio-economic capacities need to be strengthened to plan for the future for coral reefs and people.

Rapidly achieving net zero carbon emissions is indispensable, and so is the effective implementation and financing of existing management solutions. Additionally, innovation in these three science areas is critically needed to improve our 'last-minute' chances to assist transitions to better-adapted ecosystems throughout the coming decades, slowing functional losses and promoting biodiversity, justice and human wellbeing [7].

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