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Options for managing impacts of climate change on a deep-sea community

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The deep sea hosts some of the world's largest, oldest, and most sensitive ecosystems. Climate change and ocean acidification are likely to have severe implications for many deep-sea ecosystems and communities, but what, if anything, can be done to mitigate these threats is poorly understood. To begin to bridge this gap, we convened a stakeholder workshop to assess and prioritize options for conserving legislatively protected deep-sea coral reefs off southeast Australia that, without management intervention, are likely to be severely degraded within decades as a result of climate change. Seventeen possible options were explored that span biological, engineering and regulatory domains and that differed widely in their perceived costs, benefits, time to implementation, and risks. In the short term, the highest priority identified is the need to urgently locate and protect sites globally that are, or will become, refugia areas for the coral and its associated community as climate change progresses.

Recent instrumental data are consistent with global models that predict that anthropogenic climate change will have long-term effects on the physics and chemistry of the deep ocean. These effects include warming of Antarctic Bottom Water[1], cooling and freshening at intermediate depths at high latitudes[3] and possible warming and freshening at lower latitudes[4], declining inputs of surface-derived particulates[5] and declining carbonate ion concentrations[6]. The consequences of these changes for deep-sea ecosystems could be substantial, particularly in the light of the relative constancy of the physical/chemical environments these systems have historically experienced and the typically long life spans and generation times of the biota[7,8]. The latter potentially constrains the capacity of deep-sea organisms to evolve adaptations in the face of relatively rapid environmental changes. The scope for mitigating the impacts of climate change on these organisms and ecosystems is highly uncertain, in part due to the multifaceted nature of the threat, the sparse data on the physiology, ecology, and responses of deep-sea organisms, and uncertainties associated with forecasting deep-oceanic environments under climate change scenarios. Even if these issues could be overcome, however, the overarching concern is likely to be the severe logistical constraints of dealing with organisms and systems found kilometres below the sea surface. Are these constraints so difficult that mitigation efforts are effectively futile?

This question was explicitly addressed at a workshop of deep-sea ecologists, oceanographers and marine reserve managers that was convened in Hobart, Tasmania. The workshop focused on the potential fate and management options for deep-sea coral reef communities in the Huon Commonwealth Marine Reserve (HCMR), off southeast Australia. Among deep-sea communities, cold-water coral reefs have been highlighted as particularly vulnerable to climate change due to projected shoaling of water undersaturated with respect to aragonite, the isomorph of calcium carbonate that constitutes the coral skeleton and consequent reef matrix. Although many deep-sea taxa physiologically compensate for and calcify in undersaturated conditions[9,10], the colonial scleractinians that build the matrix seem to be particularly sensitive to low carbonate ion concentrations and rarely occur far below the modern aragonite saturation horizon[11,12]. This observation has led to predictions that the world's deep-sea coral reefs are at high risk of extinction in the near future as a result of ocean acidification[11,13].

The nature of the threat

Analyses of the HCMR reefs are consistent with this prediction. Between ≈1,000 and 1,300 m depth, the seamounts in the modern HCMR are essentially completely covered by the reef-forming stony coral *Solenosmilia variabilis* (Supplementary Fig. 1), which in turn supports the reserve's highest biodiversity[14]. The reef matrix is at least metres thick, accumulates at a rate of about 0.3 mm yr^{-1}, and has been present since before the Last Glacial Maximum[15]. Directly measuring the impacts of climate change on this reef requires long-term monitoring (Supplementary Fig. 2). In the interim, we assessed the magnitude of the threat by determining the environmental tolerance ranges of *S. variabilis*, using a suite of direct and indirect methods, and then mapping these tolerances ranges with respect to future ocean conditions as predicted by a state-of-the-art regional geophysical model (Supplementary Information). Multiple lines of evidence suggest minimum values for reef development for temperature and carbonate saturation state (Ω_{arag}) of ≈2.5 °C and 0.9 (that is, water 10% undersaturated with respect to aragonite), respectively. Our analyses also suggest that the coral rarely occurs in the South Pacific at water temperatures higher than 7° C. Mapping these constraints on to modern oceanographic conditions captures the known distribution of live *S. variabilis* around southern Australia (Fig. 1a); all samples were collected at sites with a habitat suitability predicted to be >80%, qualitatively validating the approach. The distribution of areas suitable for reef development in 2099 is shown in Fig. 1b for the range of possible carbon emission scenarios (Representative Concentration Pathways; RCPs) adopted by the IPCC. The scenarios range from very optimistic (RCP2.6; emissions peak in 2020 and then decline) to moderately optimistic (RCP4.5; emissions peak in 2040 and then decline) to less optimistic (RCP8.5; emissions continue to increase throughout the twenty-first century). Even under the moderately optimistic scenario, by the end of the century low carbonate saturation levels alone severely reduce areas with a habitat suitability >80%; at RCP8.5, they are eliminated completely, other than a small stretch of soft-sediment shelf edge adjacent to Western Australia. Imposing an upper temperature tolerance of 7 °C. essentially eliminates all habitat with a suitability >40% by 2099 (Fig. 1). Seamount peaks, which might logically be considered refugia from shoaling undersaturated seawater, become too warm for the coral to survive (Supplementary Fig. 8). In all

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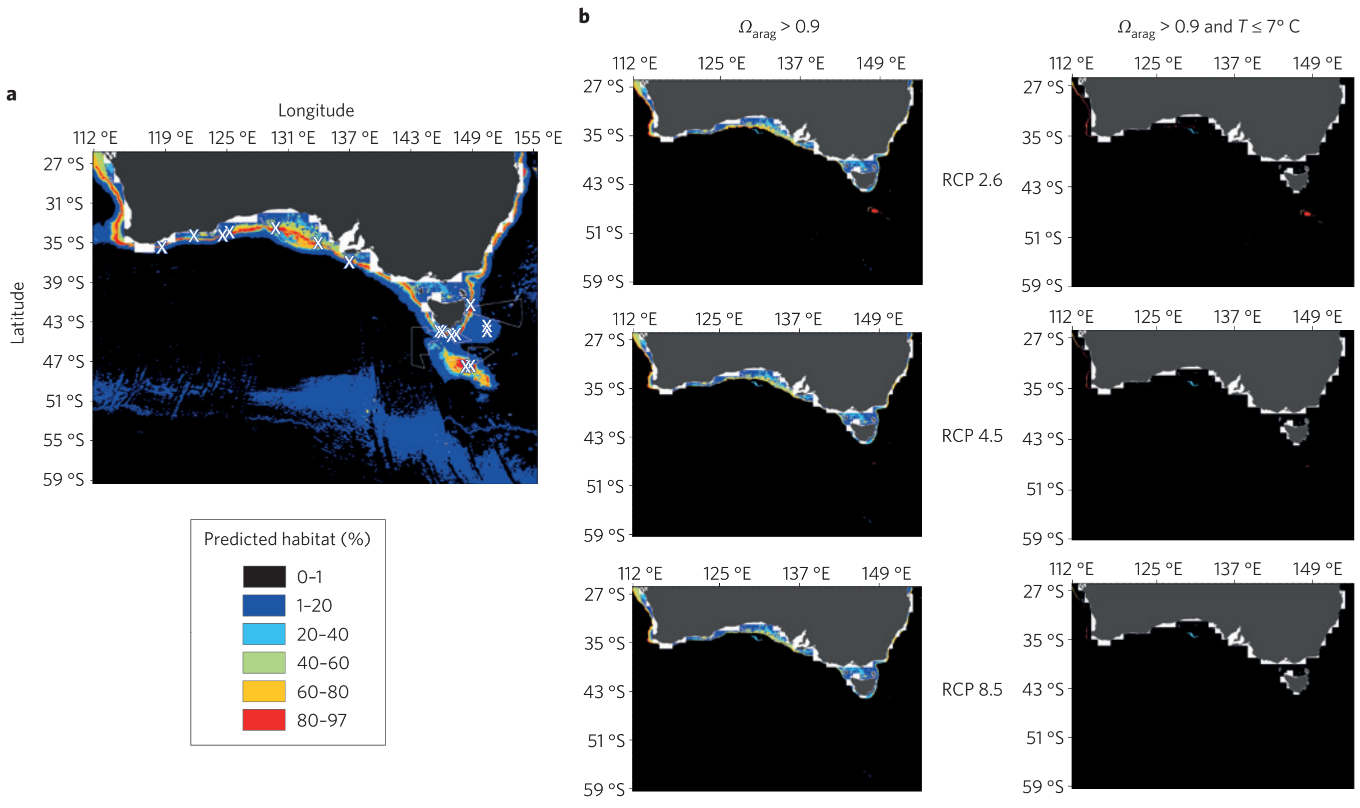

Figure 1 | Projected impacts of cliamte change on habitat suitability for *S. variabilis*. a, Modern (2009) distribution of habitat suitability in southern Australia as predicted by the global Maxent model, scored as the per cent likelihood that the habitat will be suitable for the species, compared with observed occurrences of the live coral (white crosses) and the locations of the Australian Commonwealth Marine Reserves (irregular areas outlined in white). **b**, Distribution of suitable habitat predicted for 2099 under a range of possible RCP scenarios from the IPCC, with the distribution of the coral constrained by $\Omega_{arag} > 0.9$ alone (left column), and in combination with an upper temperature limit of ≤7.0 °C (right column). RCP2.6 is the most optimistic scenario, assuming that CO_2 emissions decline substantially after 2020; RCP4.5 assumes emissions peak in 2040 followed by a decline; and RCP8.5 assumes anthropogenic atmospheric CO_2 emissions continue to rise through to 2100.

three scenarios, aragonite saturation levels fall below that required for reef development ($\Omega_{arag} < 0.9$) between 2060 and 2080; by 2099, at the depths of the modern reef, they fall below the level apparently required for the coral to even survive ($\Omega_{arag} < 0.84$) (Supplementary Fig. 8). Although these predictive models inevitably suffer incomplete process understanding of global climate change and its impacts of deep-water circulation, chemistry and physics[16] and the mechanisms that might underpin or mitigate a taxon's response to those changes[17], the predicted fate of the HCMR reef appears to be robust and dire.

What are the options?

This specific and tangible threat focused the workshop discussion: are there any practical options open to the HCMR managers to 'save' a reef more than a kilometre below the surface in the face of climate change? The procedures used to answer this question follow those recommended by the IPCC[18], as expanded upon by Marshall *et al.*[19] and Hobday and colleagues[20]. The process involved three steps. First, during a one-day workshop, a group of 13 participants — including deep-sea biologists, oceanographers, HCMR managers and a risk analyst — discussed the results of our analyses, jointly developed a list of options that could be undertaken to reduce or mitigate the impacts of climate change on the reef ecosystem (Supplementary Table 1), and produced a scoring system to assess the practicality of each option. Participants were asked to list all possible options, that is, to not withhold a suggestion *a priori* because it seemed impractical. The scoring system involved a set of ten agreed-upon and discussed cost, benefit and risk attributes (Supplementary Table 2). Cost attributes included initial and ongoing expenses and time constraints to implementation (that is, an element of the support required before the option could be implemented). Benefit was scored in terms of persistence and scale, as well as specific benefit to the coral itself or the wider ecosystem it supported. Risk involved both the possibilities that the option would fail to achieve its planned objectives and that it might have adverse effects on the system or the manager's ability to implement alternative or complementary options. Second, the options list was circulated to regional deep-sea ecologists that were not at the workshop for further suggestions; input was also obtained through feedback from presentations at regional ocean acidification and deep-sea ecology meetings, and from a presentation and subsequent discussions at the 6th International Deep Sea Coral Symposium (Amsterdam, April, 2013). Third, to evaluate and prioritize the options, each was scored independently by fifteen of the participants and the non-participating ecologists against the cost, benefits and risks criteria detailed in Supplementary Table 2.

In total, seventeen options were suggested (Supplementary Table 1): six reduce exposure of the reef to undersaturated conditions, seven represent approaches to reduce the sensitivity of the coral or its associated biota to the impacts of acidification, and four increase the adaptive capacity of the system by reducing the impacts of other stressors or facilitating survival in other areas. Six options are engineering (E) solutions (for example, adding carbonates, adding artificial substrata), five are biological (B) solutions (for example, captive breeding and re-seeding, managing disease vectors), three involve translocating (T) coral colonies (for example, facilitating colony establishment in future refugia or replacing locally extinct specimens with possibly more tolerant conspecifics from other parts of the species' range), and three involve changes in regulatory frameworks (R) (for example, protecting in reserves potential refugia locally and globally). Average scores for each attribute for each option are given in Supplementary Table 3. Details of the scoring are provided in Supplementary Figs 9–12.

Deciding on priorities for management action depends on the lead time required for implementation and externalities such as international or national policy frameworks and budget constraints. The predictive habitat model suggests that the *S. variabilis* reef in the HCMR will be severely impacted and possibly not viable within the next 50 years, a scenario that may be exacerbated by the very slow growth rate of the coral and, possibly, infrequent natural recruitment events[21]. Engineering options were judged to be those that could be implemented rapidly, whereas biological options required the longest time to develop and implement, and in some cases (for example, genetic engineering) might not even be possible. Options that involve regulatory frameworks and translocation were judged to be intermediate and roughly equal in terms of time required for implementation. The four classes of options also differed with regard to perceived average costs (B>T>E>R, Kruskal–Wallis H = 8.26, P = 0.04), benefits (R>T = B>E; H = 8.03, P = 0.045) and risks (T>E>B>R; H = 7.61, P = 0.054). Of the three vectors, cost issues are often likely to be paramount, and may dictate that low-cost options be implemented first. Among the 17 options suggested, the three perceived to be the least costly were (1) providing artificial substrata (for example, concrete tetrapods) as structure for benthic organisms currently inhabiting the *S. variabilis* reef, (2) increasing carbonate saturation levels in the reef area by adding chemicals, for example, dumping bags of lime, and (3) modifying the boundaries of the IUCN areas, if necessary, to ensure they include projected future refugia. The use of artificial substrata as a reef substitute is unlikely to benefit the coral itself, but may benefit taxa presently associated with, but not dependent on, the live reef[22]. 'Liming' and other methods of increasing local carbonate saturation levels could be undertaken at relatively low cost (for example, fishing vessels dumping bags of lime), but was perceived as having very localized and temporary benefits, if any. Altering reserve boundaries to protect future refugia depends on such refugia being available. The forecast models provide little optimism for future refugia in Australia's Exclusive Economic Zone (EEZ).

Prioritization could also be based on triangulating among the cost, benefit and risk vectors[19]. Scatterplots of the mean scores for each option in cost/benefit space are shown in Fig. 2. Four options were scored as low cost and high benefit; of these, three were also deemed to be of low risk. All three of these highly ranked options seek to increase the system's adaptive capacity by changing regulatory/policy frameworks, to (1) minimize impacts of other anthropogenic stressors on the system, (2) maximize the likelihood of survival of the species and its associated biota at other sites globally, or (3) identify and protect possible future refugia regionally. Among all options, respondents overall perceived no relationship between the cost of an option and its expected benefits ($F_{1,16}$ = 0.05, NS) (Supplementary Figure 10), but there was a strong tendency for the most expensive options to be seen as also the most risky ($F_{1,16}$ = 4.04, P = 0.06) and the most beneficial options as the least risky to implement ($F_{1,16}$ = 19.01, P = 0.0006). The likely success or failure of an option was not the central risk issue (correlation between average benefits and risk of failure, $F_{1,16}$ = 3.25, p = 0.09). Rather, the decisive issues were impacts on a manager's ability to implement other options (correlation with average benefits, $F_{1,16}$ = 21.7, P < 0.001) and the risk of unintended adverse effects on the community ($F_{1,16}$ = 19.1, P < 0.001).

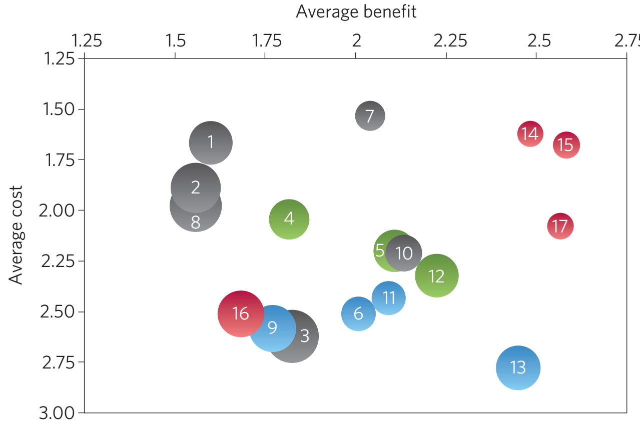

Figure 2 | Distribution of the 17 adaptation/mitigation options in cost–benefit space. Units are the average for attributes in each category, on a scale of 1 to 3 (Supplementary Table 1). Higher values represent higher perceived costs or benefits. The diameter of each circle indicates the perceived risk of adverse effects of the option (larger diameter = higher risk). Colour indicates the type of response (black, engineering; blue, biological; green, translocation; and red, regulatory/policy). Note that the low cost–high benefit options are also those with the lowest perceived risk of negative impact. Numbers correspond to options in Supplementary Table 1.

In this context, the prioritization of regulatory/policy options strongly reflects a no-regrets and inherently conservative approach among stakeholders to managing deep-sea ecosystems under threat. We note, however, that implementing these policy changes could have an undesirable outcome — protecting potential refugia could result in an unwarranted sense of 'having solved the problem', which could adversely affect availability of resources to investigate other options.

Conclusions and priorities

Basing policy decisions on stakeholder judgments can be problematic, but also often essential for issues that are urgent and need to be addressed despite large information gaps[23–25]. This is the case for the deep ocean, which is an inherently information-poor environment in which to make operational and policy decisions, and is likely to remain so for the near future. For the reasons outlined above, our stakeholders uniformly favoured changes in regulatory and policy frameworks as means of mitigating the impacts of climate change on the HCMR reefs over other classes of options. Engineering solutions were all perceived as relatively quick to implement, but also relatively expensive, (with the exception of liming the reef), small-scale and short-term. Their main value was seen as tools to delay the loss of critical ecosystem components/functions until either more effective solutions are available or the global threat is reduced. Biological solutions were perceived as expensive to develop and implement, in large part because they often involved major gaps in ecological knowledge (for example, are there major diseases of *S. variabilis*, and can they be managed?) or potentially unbridgeable technological issues (for example, can *S. variabilis* be artificially cultured cost effectively?). Translocation was a part of the mitigation suite viewed more favourably, as a tool to facilitate shifting the coral's range to emerging refugia in the light of possibly limited natural reproduction and dispersal. However, the technological hurdles involved in collecting, transporting and re-establishing colonies of a deep-water species could be significant. The process has been done successfully with *Lophelia pertusa*[26], but this colonial cold-water scleractinian inhabits much shallower depths than *S. variabilis*. If *S. variabilis* suffers long-term effects of barotrauma, which is consistent with our observations in the laboratory

(Supplementary Fig. 4), then translocating colonies over even short distances while maintaining them in a high-pressure environment could be logistically challenging. Moving colonies in the HCMR to shallower positions on the same seamount as the saturation horizon shoals could be relatively easy, but may be ineffective if seawater temperatures at these depths continue to rise. However, *S. variabilis* in the Gulf of Mexico inhabits water temperatures much higher than those in which it has been reported elsewhere (Supplementary Fig. 3). The Gulf specimens appear to be conspecific with those in the HCMR (S. Cairns, personal communication). If rising temperatures prevent colonies locally adapted to the HCMR from surviving at depths shallower than future aragonite saturation horizons, then translocating Gulf specimens to the area could be an option, though with a probable loss of the coral's global genetic diversity.

The perception that regulatory and policy options are relatively quick, inexpensive, effective and of low risk is likely to apply to threatened deep-sea ecosystems in general. However, there may often be a few regulatory and policy levers that managers can use to help mitigate or minimize climate change impacts on deep-sea ecosystems, short of regulating or banning fishing and mineral extraction as possible system stressors. History suggests that these regulatory changes will often be challenged, as they may involve forgoing access to commercially valuable resources (fishing, deep-sea mining) and compensation for rights to those resources that have already been allocated. They may also be difficult and expensive to enforce, particularly in remote high-seas locations. More fundamentally, using such tools to protect future refugia sites requires that these sites be known. This is not the case for any potentially threatened deep-sea species or community (however, see ref. 27 for an example for the shallow cold water coral, *L. pertusa*). Given the existential threat to the Australian reef, there is an urgent need to identify refugia, if any exist, at extraterritorial sites on the high seas and in other countries' EEZs and canvas options for their protection. This strategy potentially sacrifices endemic taxa, but may conserve the reef's ecosystem services regionally. We note, however, that simply protecting such areas may not suffice. Our modelling, for example, identifies a narrow strip of the shelf edge off Western Australia as a location that in the future may be oceanographically suitable for *S. variabilis*. However, the substratum there appears to be predominantly soft sediment, not suited for the coral, and it is remote from existing reefs. Ensuring the area serves as a refuge may require that hard substrate be provided for the coral to attach and translocation of live corals to seed the site. Both efforts require a commitment in excess of just changing policy settings.

Such actions ultimately depend on a political will to act. We strongly suspect that the legislative protection for Australia's deep-sea reefs, and most likely deep-sea ecologies in other national jurisdictions, is unlikely to carry much weight in the face of high costs, uncertain benefits from intervention and simultaneous demands to invest sparse resources in managing the impacts of climate change on higher-priority social and economic issues (flooding, storm damage, drought, sea-level rise, social disruption, spread of disease vectors, and so on), as well as on more conspicuous ecological ones (for example, threats to charismatic terrestrial megafauna and communities). As bluntly stated by a member of the HCMR's managing agency working in an associated, but different capacity (managing the impacts of climate change on Australia generally), "why should the government or public invest in protecting a community that few people know or care about?" If society deems that deep-sea ecosystems warrant intervention to mitigate or reduce the likelihood of significant loss of biodiversity or ecosystem services due to climate change, then national obligations may need to be enshrined in effective international instruments — of which the Convention on International Trade in Endangered Species of Wild Fauna and Flora is a good example — if they are to have a reasonable chance of being acted upon[13,28]. In that regard, a 2015 decision by the United Nations to begin the process of developing a legally binding treaty to conserve marine life in the high seas[29] is a potentially useful step forward.

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Author contributions
R.E.T. and J.M.G. conceived of, designed and analysed the results of all phases of the work, R.J.M. did the oceanographic modelling and A.J.H. led the discussion of management options and analysed the expert scoring of these options. R.E.T. undertook the analysis of environmental tolerances of *S. variabilis*, with input from J.M.G. All four contributed to writing the manuscript.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence should be addressed to R.E.T.

Competing financial interests
The authors declare no competing financial interests.