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The need for new ocean conservation strategies in a high-carbon dioxide world

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The historically unprecedented threats to the marine environment posed by increasing atmospheric carbon dioxide will probably require the use of unconventional, non-passive methods to conserve marine ecosystems. Soliciting such approaches and evaluating their cost, safety and effectiveness must be part of a robust ocean conservation and management plan going forward.

The increasing concentration of atmospheric CO_2 is thermally and chemically impacting the ocean and its ecosystems. If current trends continue, mean atmospheric CO_2 is expected to exceed 500 ppm by 2050 — a more than 80% increase above pre-industrial (pre-1750) levels[1]. This rate of increase seems to have few, if any, parallels in the past 300 million years of Earth's history[2]. By mid-century the consequences of such an increase are projected to result in a global mean warming of at least 2 °C (ref. 1) and a >60% increase in mean surface ocean acidity[3] that will have occurred over a span of just three centuries. Both the magnitude and rapidity of these changes is likely to surpass the ability of numerous marine species to adapt and survive[4]. Impacts are being and will be felt from tropical to polar oceans[3,5–7], although regional and ecosystem differences in forcings and biological responses are anticipated. Coral reef ecosystems and associated fisheries are likely to be particularly affected by the thermal and chemical changes[8–16], with trillions of dollars in economic benefit at risk globally[17–19], not to mention the threats to environmental services provided by the ocean that directly contribute to Earth's habitability. Our concern is that the specific actions to counter such impacts as identified in current policy statements will prove inadequate or ineffective. Therefore, a much broader evaluation of marine management and mitigation options must now be seriously considered.

Marine policy

Policy greatly influences the actions taken by the marine research and management communities (Fig. 1), so it is critical that policy statements accurately reflect the risks and impacts of climate change and ocean acidification, and recommend effective actions to better understand and reduce or avoid these impacts. Numerous reports and policy documents (for example, refs 19–25) have emphasized three general recommended actions to address ocean warming and acidification: (1) stabilize or reduce atmospheric CO_2 levels; (2) increase measurement and monitoring to better understand and predict the ocean's physical, chemical and biological responses to increased CO_2; and (3) preserve ecosystem resilience and adaptability by reducing non-CO_2-related environmental threats (for example, reduction of pollution, sedimentation and over-fishing, especially through the use of marine protected areas integrated with coastal zone management to control both marine- and land-based threats).

Although we agree that all of the preceding actions are essential and should continue, we are concerned that they may prove to be insufficient or not fully achievable in the time frame necessary to ensure the preservation of current marine ecosystems and their services in the face of CO_2-related threats. Given the scale and potential cost of the impacts, acting to stabilize atmospheric CO_2 and other greenhouse gases makes clear economic and environmental sense[26–29]. Yet despite growing awareness of this need and decades of effort, global anthropogenic CO_2 emissions and air concentrations continue to escalate[30,31], as have ocean temperature[32] and acidity[3]. Furthermore, the emission-reduction and mitigation actions proposed by industrialized and developing countries as part of the Copenhagen Accord are insufficient to provide even a 'medium' chance (50–66%) of limiting mean warming to 2 °C above pre-industrial levels[33]. Even if stricter emission-reduction proposals and mitigation actions are agreed to and implemented, excess CO_2 in the ocean–atmosphere system and the associated thermal and chemical effects will persist globally for many millennia after emissions have ceased[34]. For these reasons it is unwise to assume that we will be able to stabilize atmospheric CO_2 at levels necessary to reduce or prevent ongoing damage to marine ecosystems.

The measurement, monitoring and prediction of marine chemical and biological responses to increasing CO_2 (action (2) above) are clearly required to understand, anticipate and quantify their consequences for the ocean. However, such actions alone do not solve ensuing environmental problems unless used to inform and assess mitigation and conservation efforts (Fig. 1). This leads to the third commonly suggested action: preservation of marine ecosystem resilience and adaptability by reducing non-CO_2-related impacts (for example, pollution, over-fishing). There is indeed evidence that at least some marine species or genotypes will be unaffected or even enhanced by elevated temperature and acidity, or may be able to adapt through physiological changes or genetic selection[35–37]. Yet for many species, especially corals and echinoderms, the current rate of CO_2-induced environmental changes present fundamental challenges to their ability to adapt and survive. Marine life has prevailed through numerous large environmental transients in the geological record, but these episodes have resulted in significant marine species extinctions and ecosystem restructuring, with many marine groups existing as rare members of fundamentally altered ecological assemblages[37,38]. Indeed, the current rate of atmospheric and ocean CO_2 change seems to have few rivals within the geological record where elevated extinction rates and alteration of marine ecosystems are evident during previous, rapid and persistent warming

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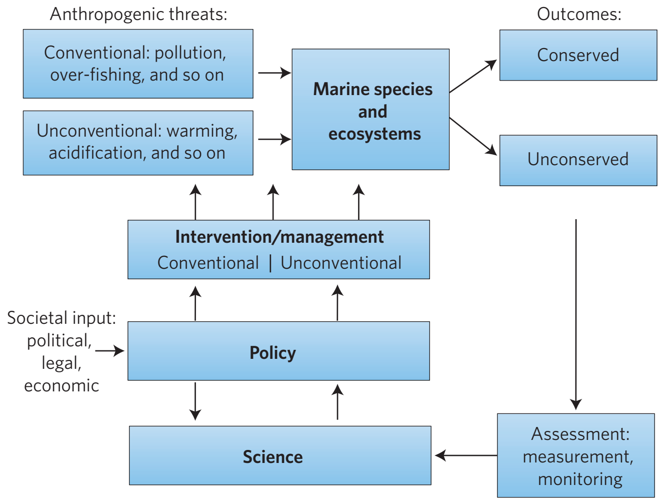

Figure 1 | Depiction of threats and outcomes facing marine biota and the possible effects of intervention and management, emphasizing both the conventional and unconventional nature of the stressors and hence the need to consider unconventional management practices. The efficacy of such approaches can be tested at small experimental scales providing feedback to marine science, policy and management. At any scale, assessment of outcomes provides critical input for subsequent policy, research and management actions. Societal as well as scientific inputs influence policy, and in turn policy plays a major role in directing marine science and management, for example, the research and the implementation of specific threat interventions.

and/or pH depression[2,37–39]. Marine organisms in certain locations are already negatively impacted by these extraordinarily high rates of environmental change, and may be unable to adapt to the projected future levels in specific areas[6,15,40–42].

It can be argued that preservation of species could occur via their vertical or geographical migration/dispersal to sub-lethal thermal and chemical regimes (should such regimes persist). This could, however, prove difficult given the potential distances involved and lack of connectivity between such sites. For example, reef-building corals at the northern end of the Great Barrier Reef are locally adapted to sea temperatures that are on average about 2 °C warmer than those growing 1,500 km off the southern end of Great Barrier Reef[8]. In this case, to keep up with sea temperatures that are likely to increase by 2 °C by the end of the century, corals (and indeed coral reef ecosystems) would have to move southward at a rate of around 15 km per year. Although there is evidence that coral species can migrate to higher latitudes over relatively long distances and relatively short time frames[43,44], such events are rare and it seems highly unlikely that a complex ecosystem such as a coral reef (with ecosystem services intact) can migrate 15 km per year.

Therefore, relying on species' natural resilience, adaptability and mobility to overcome global CO_2 impacts would seem risky at best, regardless of the benefits of reducing non-CO_2 anthropogenic stressors using conventional, passive conservation practices. Once CO_2-induced temperature and acidity tolerance thresholds for a given species are crossed, there can be no quick return to tolerable conditions, barring active environmental intervention. In the case of ocean chemistry, the time frame for return to previous conditions is measured in many thousands of years.

For these reasons, we concur with Côté and Darling[42] and with Riegl and Purkis[45] that maximizing resilience and adaptation solely through reliance on conventional marine conservation strategies (for example, marine protected areas that seek to control non-CO_2 stressors) runs the risk of failure. Recent evidence suggests that these passive management methods are already proving inadequate in many areas[46–51]. It is therefore time for the marine science, management and conservation communities to ask a fundamental question: if stabilization of atmospheric CO_2 at safe levels cannot or will not be achieved, and if critical marine species and ecosystems prove not to be resilient or able to adapt to elevated temperature and changing ocean chemistry, what are our options, if any, for protecting marine organisms and ecosystems?

Marine conservation options

At present, we do not know the answer to the preceding question, and apparently few people have asked it, as evidenced in existing policy statements. A number of published ideas may begin to point the way to useful and effective strategies (Table 1). In particular, various methods for reducing or mitigating thermal stress in corals have been proposed or demonstrated. For example, efforts to artificially shade sections of a reef during periods of thermal stress using buoyant shade cloth have been applied on the Great Barrier Reef. Light exacerbates the effect of heat stress and causes reef-building corals to bleach. Consequently, shading corals can reduce the extent of coral bleaching[52,53]. Low-voltage direct current has been proposed for stimulating coral growth and even mitigating coral bleaching and mortality[54,55], with caveats[56]. Another mechanism for avoiding thermal stress is the possible use of wave- or tidal-powered artificial upwelling, which can bring cool, nutrient-rich deep water to shallow habitats[57,58]. Such approaches, however, are only likely to be useful at small spatial scales. Alternatively, global-scale solar-radiation management has been considered, but carries with it significant risks and uncertainties[59].

Actively assisting biological resilience and adaptation through protective culturing, selective breeding or genetic engineering may also be useful. Marine organisms display different susceptibilities to thermal stress within and among species[60], therefore selective breeding of more-resilient species or individual organisms may help mitigate impacts. This may involve selecting corals (symbionts and host) that are less sensitive to thermal stress[61,62]. Finally, it may be necessary to consider constructing refuges for impacted ecosystems, artificially storing genetic material ('gene banks') or other *ex situ* methods to prevent permanent loss of genetic diversity[63].

Thermal history has been identified as an important factor affecting coral reef resistance to elevated temperature[9,64]. For example, coral communities that have been pre-exposed to high temperatures have demonstrated less sensitivity to coral bleaching compared with untreated corals[65,66]. High temperature variability has also been shown to reduce sensitivity to thermal-stress events on coral reefs[64], although this increased hardiness to temperature is insufficient to compensate for projected increases. As scientific understanding improves regarding the physiological drivers of differential susceptibility and recovery in marine organisms in response to climate-related stresses, the ability to selectively breed, culture or genetically engineer less susceptible organisms may become a viable management strategy. It seems highly unlikely, however, that this strategy has the potential to be scaled-up to include the vast numbers of marine species and ecosystems that will be impacted.

A number of the preceding management approaches addressing thermal stress might also have potential to mitigate the impacts of ocean acidification. For example, a commercially and ecologically important estuarine mollusc (Sydney rock oyster; *Saccostrea glomerata*) reared in increased CO_2 was demonstrated to be more resilient to ocean acidification than wild populations[67], implying that this species could be actively 'toughened' to withstand acid stress. A potentially less biologically stressful approach to acid mitigation would be to locally or regionally maintain or manage ambient ocean chemistry. Such methods might include the addition of globally abundant base minerals (carbonates or silicates) to the ocean[68–70]. This could act to neutralize CO_2 acidity and increase the carbonate saturation state — a critical parameter for marine biological

Table 1 | Examples of conventional and unconventional conservation methods, and their potential to address the global stressors of temperature, CO_2 acidity, and excess atmospheric CO_2.

Conservation method	Stressor addressed			Conservation method	Stressor addressed		
Conventional:	Temperature	Acidity	Carbon dioxide	**Unconventional:**	Temperature	Acidity	Carbon dioxide
Marine protected areas and coastal zone management	?	?	?	Physical — for example, sun shading, solar-radiation management; increased upwelling	X		(X)
Pollution and watershed management	?	?	?	Biological — for example, selective breeding, artificial selection, genetic engineering; creation of refuges; artificial preservation of genetic stock	X	X	(X)
Fisheries, shipping and recreation management	?	?	?	Chemical — for example, chemical, electrochemical or geochemical modification of seawater (alkalinity addition, pH elevation)	(X)	X	X
Carbon dioxide emissions reduction — increase energy efficiency and non-fossil fuel energy use; decarbonize fossil energy	X	X	X	Hybrid and other approaches — for example, conversion of waste carbon dioxide to ocean alkalinity; storage of land crop waste in ocean; ocean fertilization	(X)	X	X

X denotes direct effect; (X) indicates possible indirect effect; ? indicates uncertain. This list is illustrative and not likely to be complete. Over time additional approaches and technologies may emerge, especially as the need for intervention increases. See text for details.

shell formation[12,71,72]. However, because of the slow reaction rates of such minerals in the surface ocean, their effects on ocean chemistry would not be immediate. Such mineral weathering reactions do naturally and effectively neutralize acidity and remove CO_2 from the ocean–atmosphere system, but only over geological timescales[34]. Various methods for accelerating such reactions have been explored including reacting seawater and carbonate minerals (limestone) with the concentrated CO_2 in flue gas or other waste streams[73,74]. The ensuing chemical (mineral weathering) reaction not only consumes waste CO_2 and thus avoids CO_2 emissions, but also generates seawater alkalinity and beneficially increases the calcium carbonate saturation state.

Kheshgi[75] proposed that limestone be thermally decarbonated (calcined) and hydrated to form a chemical base, $Ca(OH)_2$, which when added to the ocean would consume oceanic/atmospheric CO_2, neutralize ocean acidity and generate ocean calcium carbonate alkalinity. Although the carbon footprint of conventional limestone calcination significantly impacts the potential net CO_2 mitigation benefit of this approach, use of a solar calcination method[76] for the process might make this form of CO_2 and ocean chemistry management more relevant. Various electrochemical methods of accelerating mineral carbonate and silicate weathering reactions have also been proposed or demonstrated, and could be useful for both CO_2 mitigation and ocean alkalinity maintenance, especially when powered by globally abundant, non-grid renewable energy[77,78].

Finally, it would be beneficial to find safe and effective ways of preserving or enhancing the ocean's immense capacity to biologically or chemically form or sequester derivatives of atmospheric CO_2. For example, various ways of increasing marine photosynthesis have been explored to enhance CO_2 conversion and storage as sedimentary organic carbon[79,80]. There may also be ways to increase the 'storage life' of marine organic matter, therefore reducing its degradation and subsequent CO_2 recycling back to the atmosphere[81,82]. It has also been proposed that agricultural crop waste could be stored on the ocean floor, especially in anoxic zones, to increase carbon sequestration, thus reducing or eliminating carbon recycling to the atmosphere[83–85]. As previously mentioned, it is also possible through enhanced weathering reactions to chemically convert CO_2 from land-based waste streams into dissolved bicarbonates that could be added to the ocean to provide both carbon sequestration and ocean alkalinity enhancement[73,73]. All of the preceding approaches are simply offered as examples of proactive strategies to ocean management, yet few have been studied beyond the concept or laboratory stage. More ideas need to be solicited and further research is required to determine which, if any of these, could form the basis for safe and cost-effective marine conservation strategies.

An argument against such actions is that they are not feasible at scales needed to address the geographical scope of the challenges. Such approaches also raise the potential for unforeseen adverse ecological impacts[86]. Some suggest that even considering such approaches may reduce incentives to address the core problem — increasing atmospheric CO_2 (ref. 87).

We reply that although such interventions might indeed only prove practical and effective at local or regional scales, little research has been done to determine the true nature and range of possible strategies and their potential scale and effectiveness. Local-scale mitigation is particularly relevant for many tropical coastal communities who depend directly on marine resources for their food, livelihoods and well-being. For example, the potential to shade coral reefs during heat-stress events may be possible over hundreds of square metres of coral reef, which may prove crucial to the success of local tourist or fishing operations. In lieu of dealing with the core causal factor (that is, the increasing emissions of greenhouse gases), these techniques and approaches could ultimately represent 'opportunities of last resort'.

There are environmental risks in any action, passive or active, that might be undertaken. However, by seeking and carefully researching all possible mitigation strategies, we can with greater certainty quantify and compare their risk/benefit and hence make better management decisions based on this knowledge. In this regard, the establishment of decision frameworks that carefully consider the different adaptation and management options is of major importance[88] (Fig. 1).

Proactive interventions are not foreign to conservation; ecosystem-restoration efforts often employ such methods[63,89,90]. Rather than waiting for damage to occur, we suggest that research and evaluation of non-passive measures to maintain and preserve marine communities must be undertaken before the need for potentially more costly and less effective restoration arises from CO_2-related impacts. Also, failing to broadly seek and evaluate all marine management options now will jeopardize our ability to quickly and effectively respond in the likely event that such methods will be required in the future.

Conclusion

The 1992 Convention on Biological Diversity[91] states, "Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation." Indeed, in the face of our continuing inability to stabilize atmospheric CO_2 and with significant uncertainty as to marine species' resiliency and adaptability to the effects of increasing CO_2, we urge that the marine science and management communities actively solicit and evaluate all potential marine management strategies, including unconventional ones, to determine which, if any, might satisfy the Convention on Biological Diversity's call for cost-effective prevention of environmental degradation. Clearly, it is best to implement such strategies only after they have been shown to be necessary, safe and effective (that is, the socio-economic and ecological costs and benefits have been assessed[26,88]). It must also be acknowledged that short of stabilizing if not reducing atmospheric CO_2, there may ultimately be no perfect or even satisfactory conservation options for the ocean, either globally or regionally. However, now is the time to find out. We call for: (1) the solicitation of new marine management and conservation methods; (2) the evaluation of their environmental, societal, and monetary cost effectiveness; and (3) policies that support the preceding. This offers a more robust and anticipatory marine management and conservation strategy than simply hoping that CO_2 levels will stabilize at safe levels, or assuming that marine biota, however otherwise well-protected, can survive and adapt to the alternative.

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Additional information

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