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PROFILE

Taking Action Against Ocean Acidification: A Review of Management and Policy Options

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Abstract Ocean acidification has emerged over the last two decades as one of the largest threats to marine organisms and ecosystems. However, most research efforts on ocean acidification have so far neglected management and related policy issues to focus instead on understanding its ecological and biogeochemical implications. This shortfall is addressed here with a systematic, international and critical review of management and policy options. In particular, we investigate the assumption that fighting acidification is mainly, but not only, about reducing CO_2 emissions, and explore the leeway that this emerging problem may open in old environmental issues. We review nine types of management responses, initially grouped under four categories: preventing ocean acidification; strengthening ecosystem resilience; adapting human activities; and repairing damages. Connecting and comparing options leads to classifying them, in a qualitative way, according to their potential and feasibility. While reducing CO_2 emissions is confirmed as the key action that must be taken against acidification, some of the other options appear to have the potential to buy time, e.g. by relieving the pressure of other stressors, and help marine life face unavoidable acidification. Although the existing legal basis to take action shows few gaps, policy challenges are significant: tackling them will mean succeeding in various areas of environmental management where we failed to a large extent so far.

Keywords Ocean acidification · Marine ecosystems · Management · Policy · Resilience · Adaptation

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Introduction

The oceans have absorbed between 24 and 33 % of anthropogenic carbon dioxide (CO_2) emissions during the past five decades (Le Quéré and others 2009). While this uptake provides a valuable service to human societies by moderating the rate and severity of climate change, it comes at a cost for the oceans. The massive input of CO_2 generates sweeping changes in the chemistry of seawater, especially on the carbonate system. These changes are collectively referred to as 'ocean acidification' (Caldeira and Wickett 2003) because increased CO_2 lowers seawater pH (i.e. increases its acidity; Gattuso and others 1999).

Ocean acidification, 'the other CO_2 problem' (Doney and others 2009), has recently emerged as one of the largest threats to marine organisms and ecosystems (reviewed in Gattuso and Hansson 2011). Describing and quantifying the plausible consequences of ocean acidification on societies, however, remains a challenge. Those consequences will depend on interactions among and between species and ecosystems (all reacting at different rates and magnitudes), on the interaction of ocean acidification with other ocean stressors (Cocco and others 2012), and on responses of each human group affected. Nevertheless, it is clear that the speed and magnitude of acidification are threatening many marine species and ecosystems. Calcifying organisms such as coral reefs, shellfish and zooplankton are among the first potential victims. Therefore, ocean acidification will also impact various economic sectors (e.g. fisheries, aquaculture, tourism; see Cooley and Doney 2009; Narita and others 2011) and coastal communities, and may also have heavy indirect effects on much broader segments of the world economy and population.

Ocean acidification appeared on the research agenda about two decades ago (Smith and Buddemeier 1992; Gattuso and others 1999). It is now an important focal issue for the research community (Monaco Declaration 2009) and related societies (e.g. European Geosciences Union 2008; European Science Foundation 2009; Interacademy Panel on International Issues 2009). The undeniable fact is that ocean acidification is happening, and we—as an international community—must take action to mitigate and adapt to its ecological and socio-economic impacts. It is thus an appropriate time to review the available management and policy options despite the uncertainties surrounding the details of acidification impacts.

Although ocean acidification is among the key questions for biodiversity conservation (Sutherland and others 2009), most research efforts on acidification have so far neglected management and related policy issues to focus instead on understanding its ecological and biogeochemical implications. Authors tend to make only cursory references to potential responses. Among the exceptions, Harrould-Kolieb and Herr (2011) discuss the possibilities to address ocean acidification under the United Nations Framework Convention on Climate Change (UNFCCC). Kelly and others (2011) review options to mitigate local causes of ocean acidification in general, while Kelly and Caldwell (2012) identify more specifically what the State of California can do. Miles and Bradbury (2009) also have a US focus and briefly identify broad areas where effort should be made (namely research, monitoring, ecosystem-based management and understanding where changes are occurring on variable timescales) rather than concrete responses. Rau and others (2012) explore new ocean conservation strategies to preserve ecosystem resilience and adaptability facing unavoidable acidification. However, no review of management options against related policy frameworks has been done in a systematic, international and critical way. We address this shortfall here. In particular, we investigate the idea that there is more to addressing acidification than 'just' reducing CO_2 emissions, while also exploring the new opportunities that this emerging issue may bring into the on-going climate change talks.

We first examine the scientific basis of ocean acidification's causes and impacts. We then review nine types of responses, initially grouped under four categories: preventing Ocean Acidification; strengthening ecosystem resilience; adapting human activities and repairing damages. Each review of the responses covers the same scope: (i) description of the action process and how it is supposed to work; (ii) potential and limits of the action discussed; (iii) barriers and opportunities to implementation. We further discuss emergent results of the review: we weigh and reconnect the various options with one another and explore the legal andpolitical basis for action.

The Scientific Basis: Causes and Impacts of Ocean Acidification

There are two known causes of ocean acidification. By far the primary cause is the ocean's uptake of atmospheric CO_2, and there is growing evidence for secondary enhancement of CO_2-driven acidification by other pollutants in coastal regions (Cai and others 2011; Sunda and Cai 2012). In addition, the dissolution of solid-state methane hydrates from the sea floor as a consequence of ocean warming is a third (potential) cause of future acidification. We treat each of these three here, in sequence.

Uptake of Atmospheric CO_2 by the Ocean

Atmospheric CO_2 is the major driver of ocean acidification globally. Atmospheric CO_2 continues to rise: its average mixing ratio exceeds[1] 390 parts per million (ppm) which is far above the preindustrial value of around 280 ppm and a natural range of 172–300 ppm in the past 800,000 years (Lüthi and others 2008). The increase of CO_2 in the surface ocean resulting from the uptake of anthropogenic CO_2 profoundly affects the seawater carbonate system through well-known chemical reactions (e.g. Skirrow and Whitfield 1975). It lowers the pH, increases the concentration of bicarbonate ions (HCO_3^-), decreases the availability of carbonate ions (CO_3^{2-}) and lowers the saturation state of the major shell-forming carbonate minerals such as calcite and aragonite. This process is known as 'ocean acidification' because, even though the surface waters remain alkaline, seawater pH is decreasing.

Average surface water pH values[2] are in an accelerating decline: about 8.3 during the last glacial maximum, 8.18 just prior to the industrial era, and 8.10 at present. Measured trends agree with those expected from the atmospheric CO_2 increase, with uncertainties larger for the high latitudes, deep ocean, coastal areas, and marginal seas. The basic chemistry of ocean acidification being well understood, future projections are quite reliable for the surface open ocean for a given atmospheric CO_2 trajectory (Orr 2011). Those based on the International Panel on Climate Change (IPCC) scenarios give reductions in average global surface pH of between 0.14 and 0.35 units over the twenty-first century, which means surface pH may reach 7.8 in the year 2100 (Orr 2011). However, climate-carbon cycle feedbacks such as those related to changes in temperature, stratification and ocean circulation, as well as to the marine biological cycle, further modify the distribution of natural and anthropogenic carbon. These feedbacks are projected to somewhat lower the uptake rate of anthropogenic carbon by the ocean (Friedlingstein and others 2006; Plattner and others 2008) and to redistribute carbon within the ocean (Plattner and others 2001; Frölicher and Joos 2010). A delayed uptake of anthropogenic CO_2 leads to higher CO_2 and acidification in the surface ocean and to a delayed increase in carbon and ocean acidification in the deep.

Despite anthropogenic CO_2 emissions being the primary driver of acidification, the chemical and biological impacts of ocean acidification would continue to intensify for many years thereafter even if emissions were halted altogether by the end of this century (Joos and others 2011). Nevertheless, mitigating CO_2 emissions would substantially ease the trajectory of acidification over the course of the twenty-first century (Joos and others 2011). Different temperature and circulation patterns create spatial variability in the timing and severity of acidification: for example, model projections and observations indicate that aragonite undersaturation is imminent and will become of large-scale extent by about 2020 in the Arctic Ocean (Steinacher and others 2009) and 2050 in the Southern Ocean (Feely and others 2009).

Coastal Acidification due to Additional Pollutants

Several anthropogenic inputs also exacerbate the effects of ocean acidification at smaller spatial scales (Feely and others 2010; Cai and others 2011). These inputs act disproportionately along coastal margins where anthropogenic stressors are most acute and where oceanographic patterns such as upwelling or incomplete flushing occur, especially in bays and estuaries.

Mechanisms for this locally intensified acidification are known: while Hunter and others (2011) show a negligible equilibrial effect of deposition of atmospheric NO_x and SO_x, nitrogen and phosphate runoff from agricultural, industrial, urban and domestic sources causes eutrophication, triggering population spikes of algae or heterotrophic plankton (Cai and others 2011). In the case of algal blooms, surface waters experience a surge in $p(O_2)$ and in pH, while stratified bottom waters accumulate decaying organic matter and rapidly acidify. In addition, terrestrial sediments may bury or shade productive benthic habitat, triggering anoxic and acidified conditions.

The relative importance of each of these mechanisms—as well as the importance of each relative to that of global CO_2—is a matter of active research, but it seems clear that non-CO_2 inputs can contribute significantly to the overall acidification threat in some coastal regions (Feely and others 2010, 2012; Cai and others 2011). Understanding and mitigating these secondary causes of acidification is especially important in light of the fact that marine organisms respond to changes in local conditions, and thus are more likely to be sensitive to peaks in $p(CO_2)$ or pH than to long-term shifts in average values for these parameters (Barton and others 2012).

Models by Borges and Gypens (2010), for example, document the significant effects that nutrient inputs can have on coastal ocean chemistry. They show that changing phosphate loads from terrestrial sources could shift coastal surface waters from net heterotrophy to net autotrophy, with an overall effect greater than that of anthropogenic CO_2. Feely and others (2010) measure a related effect in Puget Sound, Washington, USA, showing that respiration—in part stimulated by anthropogenic nutrient input—in the surface and bottom waters had a greater acidifying effect than uptake of anthropogenic CO_2. Cai and others (2011) are in accord.

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[1] It reached 394.28 ppm in December 2012, compared to 391.83 in December 2011. See http://www.esrl.noaa.gov/gmd/ccgg/trends/ Accessed on 4 April 2012.

[2] pH is expressed on the total scale throughout this paper.

Release of Methane Hydrates into the Ocean

In contrast to the above mechanisms, which are both acting at present to lower the ocean's pH, seafloor methane hydrates pose a potential threat in a more distant future. The exact inventory of methane hydrates that are currently stored in the sediments below the ocean remains highly uncertain, between 500 and 63,400 Gt C (Hester and Brewer 2009), but consensus exists that this represents a significant fraction of the amount of carbon globally stored, comparable to the amounts of other fossil fuels. Owing to high pressure and cold temperature conditions, methane today remains in stable hydrate form below 300 m (Tishchenko and others 2005). Further changes in sea level and/or deep oceanic warming could cause a transition from the hydrate into the gas phase, therefore, would allow outgassing into the overlying ocean and into the atmosphere. Since the current and near-future evolution of sea level rise remains in the range of a few decimetres (Church and others 2011), it is mainly the warming of the mid-depth and deep ocean that has the potential to significantly alter the stable conditions of methane hydrates. Microbial aerobic oxidation would then convert methane remaining in the water column, with oxygen, into CO_2 (Valentine and others 2001), thus contributing to ocean acidification.

Biastoch and others (2011) estimated the future evolution of methane hydrates bound below the Arctic Ocean using a hierarchy of atmosphere, ocean/sea-ice and geophysical models (2011). In a global warming scenario (1 % increase in greenhouse gases (GHGs) concentrations until doubling, Park and others 2009) the authors projected the evolution of near-bottom oceanic temperatures for the next 100 years. The resulting warming was spatially heterogeneous and strongest in shallow and mid water depths; thereby potentially shifting methane hydrates around 500-m depth into the gas phase. However, as shown by a simulation of the gas hydrate stability zone, temperature changes slowly progress into the sediment, therefore, limiting the release within the next 100 years. Within that time span the amount of released methane is too small to further enhance global warming. However, in limited areas around the rim of the Arctic Ocean it may be large enough to cause ocean acidification of the near-bottom ocean. Assuming a significant amount of methane (50 %) to be released into the water column and weakly diluted with adjacent waters, regionally limited pH decreases would be up to 0.25 U. Due to the inertia of the ocean and the delayed intrusion of heat into the sediments, the process of methane release would be irreversible and would continue for a long time, even after global warming has eventually stopped.

Evidence for methane outgassing into the water column has already been reported for the Arctic Ocean (Westbrook and others 2009), a region that stands out with the highest temperature changes in global warming (Solomon and others 2007). However, it remains unclear to which extent this is a new trend or part of the natural carbon cycle. Ice core data show that atmospheric methane concentrations were similar (about 700 parts per billion) during the pre-industrial period compared to the last interglacial, although palaeodata and model results consistently suggest that summer temperatures in high northern latitudes were up to 5 °C warmer than today (Jansen and others 2007). This makes it rather unlikely that a massive loss of methane from the northern high-latitude ocean to the atmosphere will occur in this century.

There is, therefore, no consensus, as of today, as to whether the dissolution of methane hydrates due to ocean warming represents a real and significant threat to the oceans in the course of the twenty-first century. We include it in this review for the sake of completeness but do not discuss it in great detail.

Impacts of Ocean Acidification on Marine Organisms and Ecosystems

Whatever its cause, ocean acidification can have a wide range of biological effects, through two main mechanisms. First, pH plays a key role in several physiological processes and many intracellular enzymes that control cellular physiology are pH-sensitive. The pH of body fluids in animals and the intracellular pH of various organs or unicellular organisms are tightly regulated, but regulatory mechanisms are energetically expensive and can be overwhelmed. The second mechanism occurs through changes in the concentration of molecules that are themselves substrates in key physiological processes. For example, carbon dioxide and bicarbonate are used in photosynthesis and carbonate is a building block of shells and skeletons made of calcium carbonate. Hence, ocean acidification can stimulate primary production since the concentrations of both CO_2 and HCO_3^- are larger at lower pH (see Riebesell and Tortell 2011). It also often decreases calcification (the construction of shells and skeletons; Andersson and others 2011; Riebesell and Tortell 2011), and generally stimulates nitrogen fixation in cyanobacteria (Riebesell and Tortell 2011). This suggests that highly calcium carbonate-dependent ecosystems—such as coral reefs and oyster and mussel beds—are particularly vulnerable.

However, these generalities mask the fact that the magnitude of species-specific physiological effects is highly variable and, in few cases, even the sign of the response may vary (Kroeker and others 2010). For example, there is evidence that the same species may differ in sensitivity among lifestages (e.g. with enhanced sensitivity among larval stages; Kurihara and others 2008), among different strains of the same species (Langer and others

2009; Parker and others 2011), and dependent on their previous exposure (e.g. carry-over effects; Hettinger and others 2012; Parker and others 2012). This variability underlies the observation that forecasting ecosystem-level effects of ocean acidification is substantially more difficult than understanding the highly variable species-level effects, given that the ecosystem is an emergent property of individual species (Kelly and Caldwell 2012).

Preventing Ocean Acidification

Consistent with the causes of acidification reviewed above, we identify three main ways to prevent ocean acidification from worsening: limiting CO_2 concentration in the atmosphere, either by reducing emissions or by removing CO_2 from the atmosphere once emitted; reducing coastal pollutants that exacerbate CO_2-driven acidification; and limiting ocean warming (hence potentially avoiding the release of methane hydrates over the longer term) either by reducing emissions of GHGs or by managing solar radiation.

Limiting CO_2 Concentration in the Atmosphere

Reducing CO_2 Emissions

The most obvious way to limit CO_2 concentration in the atmosphere is to reduce its emissions.[3] CO_2 and other GHGs have been the primary target of the UNFCCC since its adoption in 1992, and of all subsequent climate talks. International climate negotiations, however, have failed to reach a legally binding, long-term agreement that would include all major and emerging economies to reduce CO_2 and other GHG emissions. During the seventeenth Conference of the Parties (COP) in 2011, Parties agreed to a second commitment period for the Kyoto Protocol (2013-1017). However, a number of significant countries, including Canada, Japan and Russia, opted out and the US maintained its reticence to participate.[4] Given the emissions of these nations—they are four of the top ten CO_2 emitters[5]—it is thus questionable whether this second commitment period will result in significant emissions reductions. Parties to the UNFCCC also reconfirmed at COP 17 national non-binding targets pledged as part of the 2009 Copenhagen Accord. These pledges are, however, not ambitious enough to limit global average temperature rise to >1.5–2 °C above pre-industrial levels (UNEP 2010)—the politically accepted limit not to trespass so as 'to prevent dangerous anthropogenic interference with the climate system[6]'.

Nonetheless, even with greater commitments, it would still be unclear whether the global target of 2 °C would effectively address ocean acidification. First, it is still unclear what level of atmospheric CO_2 may constitute a 'safe' level with respect to ocean acidification. Second, climate talks deal with cumulative radiative effects and do not prioritize reductions in any one gas. The Kyoto Protocol, for example, creates a common denominator for GHGs by expressing emissions of six GHGs (or groups thereof) in units of CO_2 equivalents. The focus on reducing the equivalent concentration of atmospheric GHGs to limit global temperature rise does not account for non-thermal impacts of each of these gases (Caldeira and Wickett 2003; Kleypas and others 1999; Orr and others 2005). Ocean acidification is thus largely absent from most policy discussions of GHG emissions reductions (Harrould-Kolieb and Herr 2011).

The potential of CO_2 emissions reductions to prevent further ocean acidification is immense in absolute terms since atmospheric CO_2 concentration is the main global driver of acidification. Limits, though, exist. The future effectiveness of CO_2 emissions reductions in preventing ocean acidification is limited by geochemical inertia, as present emissions levels will lock-in minimum changes to ocean temperature and pH for centuries to come (Joos and others 2011; see also 'Removing CO_2 from the atmosphere' Section). Further, the effectiveness of emissions reductions is necessarily limited by other causes of acidification, namely coastal pollutants and the potential release of methane hydrates. However, neither limit contradicts the importance of reducing CO_2 emissions, instead only increasing the urgency to do so.

CO_2 emissions presently come mostly from fossil fuel burning (about 90 %, primarily from the energy supply, industry, transportation and building sectors) as well as land use and land-use change (about 10 %, especially tropical deforestation) (IPCC 2007). Reducing CO_2 emissions from fossil fuel burning, particularly in developed and emerging countries, is technically and economically feasible (European Commission 2011; Stern 2006), but it involves complex transitions that are currently only slowly—if at all—under way. Particularly important for CO_2 emissions reductions are measures to improve energy conservation and energy efficiency and the large-scale deployment of existing (or future) low-carbon or carbon-free energy production and distribution technologies. This

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[3] We include Carbon Capture and Storage (CCS) at the source as one of the methods available, in principle, to reduce CO_2 emissions. However, discussing the specific potential, sustainability and environmental impacts of CCS is beyond the scope of this paper.

[4] The U.S. never ratified the Kyoto protocol.

[5] See http://edgar.jrc.ec.europa.eu/index.php.

[6] UNFCCC, Article 2.

can also imply changes in geographic settlement patterns, urban planning and public transit.

Land-use change emissions are estimated to have decreased by about 25 % in 2000–2010 compared to 1990–2000.[7] This is related to a decline in both temperate and tropical forest deforestation rates. For tropical forests this is at the same time a result of more proactive policies and ironically of the continuous reduction of their remaining area—and hence of the diminishing potential for deforestation. Should funding going towards reducing emissions from deforestation and forest degradation continue to increase[8] (especially via contributions to the Green Climate Fund established at UNFCCC COP 16), there are good reasons to anticipate that CO_2 emissions due to land-use change will not grow or will continue to decline in the future.[9]

Broadening the scope of GHG policy discussions to focus not only on the thermal impacts of emissions but also on acidification would at least allow nations to incorporate the effects of ocean acidification into their mitigation strategies (Harrould-Kolieb and Herr 2011). This broadening would in principle necessitate a shift in priorities to place a greater emphasis upon reductions of CO_2 in preference to non-CO_2 GHGs. This would in turn require reducing the conversion factor used to make non-CO_2 and CO_2 emissions equivalent for emissions trading, and could also lead to separate emission targets for CO_2 and non-CO_2 agents. The UNFCCC has launched a process to periodically assess the adequacy of the long-term global goal (currently set at an average surface temperature of 2 °C above preindustrial levels[10]), which provides one point of entry for the international community to reflect on the equivalence (or lack thereof) between CO_2 and non-CO_2 GHG emissions with respect to ocean acidification. Nevertheless, adding ocean acidification as one more argument for stringent and rapid CO_2 emissions reduction, coupled with a push for decisions on preferential treatment of one GHG versus others as well as development and agreement on new thresholds, would make currently highly politicized international negotiations even more complex. The outcome of such an endeavour would thus be highly uncertain.

Removing CO_2 from the Atmosphere

Besides reducing CO_2 emissions, some climate-engineering techniques also have the potential to prevent ocean acidification; chief among these is CO_2 removal. The Royal Society (2009) reviewed the effectiveness, timeliness, safety and cost of five of these methods that aim at enhancing uptake and storage by terrestrial and oceanic biological systems, or at using engineered (physical, chemical, biochemical) systems. These included:

- Land-use management to protect or enhance land carbon sinks;
- The use of biomass for carbon sequestration as well as a carbon neutral energy source;
- Enhancement of natural weathering processes to remove CO_2 from the atmosphere;
- Direct capture of CO_2 from ambient air. Typical examples include the so-called 'artificial trees' which mimic the function of natural trees whereby leaves pull CO_2 out of the air as it flows over them,[11] by bringing ambient air in contact with chemical sorbents;
- The enhancement of oceanic uptake of CO_2, for example by fertilisation of the oceans with naturally scarce nutrients.

Enhancement of oceanic uptake of CO_2, especially, has been thoroughly debated. Ocean fertilisation can be undertaken by addition of the micronutrient iron to High-Nutrient-Low-Chlorophyll (HNLC) waters, where a number of natural and artificial iron fertilisation experiments have shown that low ambient iron concentrations limit phytoplankton growth. In situ iron fertilisation experiments have yielded enhanced biological production in all major HNLC areas such as the equatorial Pacific, the Southern Ocean and the subpolar North Pacific (de Baar and others 2005), but paleodata (Röthlisberger and others 2004) and modelling studies (Joos and others 1991; Sarmiento and others 2010) consistently suggest that ocean iron fertilisation (OIF) has a limited and temporary effect on ocean carbon uptake and atmospheric CO_2. Substantial oceanic uptake of CO_2 may be triggered only in the Southern Ocean with less than 1 GtC per year, i.e. >10 % of current anthropogenic CO_2 emissions (Oschlies and others 2010). To the extent that OIF works to sequester additional CO_2 in the ocean, it will actually amplify acidification of the waters that store the sequestered CO_2 (Denman 2008). As the waters that contain the sequestered CO_2 are subducted into the deeper layers of the global ocean, they will also transport the associated signal with reduced pH levels. Nevertheless, the OIF-induced reduction of atmospheric pCO_2 would be felt in the surface waters outside the fertilised area as well, and would decelerate ocean acidification in tropical near-surface waters

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[7] http://www.globalcarbonproject.org/carbonbudget/10/hl-full.htm Accessed on 21 May 2012.

[8] http://www.reddplusdatabase.org Accessed on 31 January 2013.

[9] Emissions from land use and land-use change are projected to stay around current levels or to decline over this century for the four Representative Concentration Pathways, the scenarios assessed in the forthcoming Fifth Assessment Report of the IPCC.

[10] Decision 1/CP.16, paragraphs 4 and 138–140: http://unfccc.int/resource/docs/2010/cop16/eng/07a01.pdf#page=2; Decision x/CP.17 para 157–167: http://unfccc.int/files/meetings/durban_nov_2011/decisions/application/pdf/cop17_lcaoutcome.pdf.

[11] http://news.bbc.co.uk/2/hi/6374967.stm.

(Oschlies and others 2010). By exacerbating acidification in some areas and decreasing it in others, OIF would hence merely impact the distribution of losers and winners (be they species likely to be harmed vs. to benefit as a result of the changed chemical environment, as in Fabricius and others 2011, or marine resources-dependent human groups)—with overall impacts likely to weigh in the negative. Chisholm and others (2011) conclude that the known impacts of and uncertainties related to fertilisation far outweigh hypothetical benefits, while Güssow and others (2010) argue that more research is needed to clarify this. In any case, such activities are today forbidden by international law except for necessary scientific research (see 'Legal and Political Basis for Action'). Hence we exclude OIF from the solutions bundle here. Direct injection of CO_2 into the deep ocean would work similarly and is rejected as well from the range of options we review.

Besides OIF, the overall potential of CO_2 removal techniques is impossible to assess precisely at this stage but seems unlimited in theory. Of the techniques assessed by the Royal Society (2009), 'none has yet been demonstrated to be effective at an affordable cost, with acceptable side effects', and Williamson and Turley (2012) find that they hold little promise in terms of the maximum reduction in atmospheric CO_2 they might realistically achieve. But depending especially on safety and cost conditions, CO_2 removal theoretically has the potential to allow a future reduction of atmospheric CO_2 concentration—something reducing emissions alone cannot achieve.

CO_2-removing methods that do not perturb natural systems nor require large-scale land-use change are likely to have fewer impacts and be more socially acceptable (The Royal Society 2009). In some cases, practical barriers will also limit the use of climate-engineering techniques (e.g. scarcity and cost of raw material such as sodium hydroxide, as well as the energy and emissions required to acquire and transport the necessary materials). Conversely, incentives for a technology-based fix will stem from the reluctance of societies to envisage shifts in current development models: technological options, such as those allowing direct capture of CO_2 from ambient air, may offer business-as-usual solutions that, however expensive as of today, will become ever more acceptable, profitable and necessary if we continue failing to reduce CO_2 emissions. This is why calls to evaluate the potential, costs and benefits of geoengineering solutions to ocean acidification grow louder every day.

Reducing Local Factors of Ocean Acidification

Taken together, the studies reviewed in 'The Scientific Basis: Causes and Impacts of Ocean Acidifciation' Section also provide a rationale for using controls on nutrient inputs as a policy lever for mitigating acidification in the coastal ocean.

The potential for nutrient controls and other local- and national-scale pollution control measures clearly depends upon the relative importance of non-CO_2 inputs in driving ocean acidification. For the open ocean, which is likely to experience the effects of coastal stressors less directly, such policy levers are probably both less important (likely to have less effect) and less feasible (given the governance issues of the high seas). For the coastal oceans—for example, to the seaward limit of countries' Exclusive Economic Zone (200 nautical miles)—policy action on pollution controls could be of critical importance in areas where the chemical effects of terrestrial inputs rival CO_2-driven acidification (see 'Coastal Acidification due to Additional Pollutants'). Where local and national economies rely heavily upon $CaCO_3$-dependent ecosystem services, for example shellfish farming and coral tourism, reducing local acidifying factors could produce results both faster and in a more politically feasible manner than would a global CO_2 solution alone. One small example might be reducing nutrient inputs while co-locating shellfish farming or a similar $CaCO_3$-dependent activity with seagrass beds (which increase growth as $p(CO_2)$ rises). This would simultaneously control pollution, raise the pH and aragonite saturation state of the surrounding waters, and safeguard ecosystem services including flood control. One of the great advantages of action on local pollutants is that it has almost immediate effects on local acidification, buying time as we struggle to address the greater problem of CO_2-induced acidification.

There are no major structural barriers (i.e. posed by the nature of the action to be taken or by law) to implementing local policy actions to combat acidification. Many countries have applicable water and air quality laws and other tools at their disposal to alleviate non-CO_2 acidification in their jurisdictions (see 'Coastal Acidification due to Additional Pollutants'). However, the usual barriers surrounding environmental regulation—vested economic and property interests—remain. Surmounting these barriers will require an increased sense of urgency, as well as a willingness to pair top-down regulation with voluntary, incentive-based measures. It bears noting, however, that because coastal regions tend to be the most culturally and economically important areas of the ocean worldwide, pollutants such as eutrophying runoff are more visible—and, therefore, probably more politically tractable—than the more diffuse and global CO_2 problem.

Reducing the Risks of a Potential Release of Methane Hydrates

Reducing Greenhouse Gases Emissions Beyond CO_2

Limiting the thermal greenhouse effect to avoid potential destabilization of solid-state methane hydrates is a safeguard against the related, hypothetical acidification problem.[12] This section hence briefly addresses the reduction of non-CO_2 GHGs (CO_2 is treated in 'Coastal Acidification due to Additional Pollutants' Section), taking as examples the five other sets of compounds included in the Kyoto Protocol: PFCs, SF_6, HFCs, N_2O and CH_4.

GHG emissions continue to increase by about 3 % per year; however, some key non-CO_2 GHG emissions can be reduced considerably by purely technological changes. PFCs, which are used for air conditioning, are already being phased out: emissions decreased e.g. by 53 % in Canada (Environment Canada 2006) and 47 % in France[13] from 1990 to 2004. SF_6, mostly emitted by the aluminium and magnesium industry, or HFCs, are relatively cheap to phase out without any dramatic change to current development models (EIA 2010). By contrast, reducing N_2O emissions, which originate mainly in agricultural fertilisers, has much wider implications for agricultural intensification and food security.

Anthropogenic CH_4 emissions—another important source of non-CO_2 GHGs—have three main sources: waste, energy and agriculture. The first two sources offer interesting and socially attractive mitigation opportunities. First, emissions from urban landfills can easily be captured and used for power generation, satisfying a critical infrastructure requirement while providing important additional public health benefits. Second, CH_4 emissions in the existing energy sector can be reduced significantly simply by hunting down leakages, a mitigation strategy which is likely to become more systematic as the rising price of CH_4 makes it profitable.

This short panorama shows that to the extent that we really have an acidification problem exacerbated in the long term by the rise of global temperatures, some non-CO_2 GHG emissions reductions appear technologically feasible and politically viable. However, any such measures would not be sufficient by themselves to significantly limit warming, as CO_2 will drive 58–76 % of the warming during this century (Strassmann and others 2009).

Managing Solar Radiation

In addition to reducing GHG emissions, temperatures can be influenced by either removing GHGs from the atmosphere or by managing solar radiation. Techniques to remove non-CO_2 gases from the atmosphere have not yet been investigated (The Royal Society 2009). Solar radiation management techniques do not directly reduce CO_2 or other GHGs,[14] yet they do offer the possibility of alleviating the symptoms of climate change. The Royal Society (2009) observed that solar radiation management techniques might have the potential to be affordable and feasible approaches to complement emissions reductions and CO_2 removal, but noted that solar radiation management carries with it considerable uncertainties and biophysical risks. Moreover, Williamson and Turley (2012) conclude that the effects of solar radiation management on acidification are uncertain in both their magnitude and direction.

Strengthening Ecosystem Resilience to Ocean Acidification

In addition to tackling the root causes of ocean acidification, there is an increasing interest in boosting resilience in marine ecosystems to better tolerate its impacts. Ecological resilience can be broken down into two parts: resistance and recovery (Holling 1973; Gunderson 2000; Walker and Salt 2006). Resistance is defined as the ability of a population or ecosystem to absorb a disturbance without significantly affecting their function. Recovery pertains to the ability of the population or ecosystem to quickly return to its pre-disturbance state following a perturbation (Levin and Lubchenco 2008; Palumbi and others 2008). Although the science of resilience is still in the early stages, it is important to consider whether management actions have the potential to bolster resilience to acidification given that it is already happening and is expected to continue even if CO_2 emissions are rapidly mitigated.

As of 2013, empirical studies examining population or ecosystem resilience to ocean acidification are not available. However, ecological resilience theory provides a framework for considering its usefulness for ocean acidification. For example, it has been proposed that ecosystems with higher diversity will be more resilient to environmental stress (Folke and others 2004). When there is a wide range of species within an ecosystem, then there is likely to be a wide range of responses to ocean acidification and, therefore, a greater likelihood that the ecosystem will contain species that can withstand the disturbance (i.e. the insurance hypothesis: Naeem and Li 1997; Yachi and Loreau 1999). Following this logic, management actions that promote diversity (e.g. marine protected areas) could theoretically promote resilience to acidification-related species loss (West and Salm 2003; McLeod and others 2009), although this does not necessarily address population-level resilience.

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[12] Although slowing the warming effect would also slightly favour the solubility-driven oceanic uptake of CO_2.

[13] www.citepa.org.

[14] Though lower surface temperatures lead to slightly higher solubility-driven GHG uptake by the ocean; Matthews and Caldeira 2007.

At the population-level, the cumulative impacts of multiple stressors are rarely additive (Crain and others 2008, Darling and Côte 2008) and additional stressors can exacerbate the effects of ocean acidification on some species (Lefebvre and others 2012; Roberts and others 2013). Thus, management of local stressors, such as nutrients and toxins, could increase the population-level resilience to acidification. In addition, it has also been shown that the effects of ocean acidification are reduced in well-fed, healthy organisms compared to those that are food limited (Thomsen and others 2012; Holcomb and others 2010). Thus, protecting healthy organisms in food-replete conditions may strengthen population resilience.

Another consideration specific to ocean acidification is whether the management of fishing and nutrient pollution could enhance the resilience to potential acidification-mediated phase shifts. Reduced growth rates of calcified species due to acidification (Kroeker and others 2010) could impede their recovery from disturbance events caused by other stressors. This may be especially important where the calcified species are in competition with fleshy algae, which may grow more quickly in the same conditions (Connell and Russell 2010; Kroeker and others 2013). Anthony and others (2011b) modelled coral reef recovery from bleaching events on reefs affected by overfishing and nutrient pollution, and found that acidification synergistically increased the risk of phase shifts to algal-dominated ecosystems (Mumby and others 2007; Anthony and others 2011b). In turn, robust fish populations and lower nutrients lessened the impacts of acidification on the ecosystem by limiting nutrient-enhanced growth rates of fleshy algae and increasing grazing by fish. Therefore, the management of herbivore populations and nutrient pollution may prove an important tool for strengthening ecosystem resilience (Hughes and others 2003; Folke and others 2004; Anthony and others 2011b; Kelly and others 2011; McLeod and others 2013).

The evidence for human-mediated increases in resilience is sparse (but see Micheli and others 2012), and building resilience is not a solution to ocean acidification per se. Ultimately, increasing resilience will only be effective as a harm-mitigation technique if it is accompanied with other measures and in particular, with significant cuts in CO_2 emissions. Barriers include all those previously identified to marine biodiversity protection, including funding, diverging interests and capacity. Moreover, in order to use MPAs—often cited as a resilience-building tool for managing the effects of ocean acidification—the reserves would need to be carefully sited to avoid hotspots of acidification (Hofmann and others 2011; Kelly and others 2011). Finally, it is important to consider the potential for evolutionary adaptation among key species to acidification (Sunday and others 2011; Lohbeck and others 2012), and site MPAs in areas that protect potential genetic diversity or target locally adapted populations.

Adapting Human Activities in Anticipation of or Reaction to Ocean Acidification

It is now widely acknowledged that climate change adaptation and mitigation are complementary, rather than alternative, strategies. Paraphrasing the IPCC (Adger and others 2007), we can define adaptation to ocean acidification as the adjustment of natural or human systems in response to present and future acidification or to its effects, in order to mitigate the damage or to exploit beneficial opportunities. Adaptation to ocean acidification, therefore, covers a wide range of potential actions, and some such measures will be inevitably necessary given the inertia of past CO_2 emissions' effect on present and future ocean acidification.

Practical examples of adaptation are still scarce. Revenue-generating activities like fisheries or aquaculture will have opportunities to adapt to an acidified ocean as the knowledge base improves and impacts become more noticeable, but uncertainties are high as regards associated costs and benefits. There is at least one available example regarding aquaculture in Oregon and Washington, USA, a region in which seasonal upwelling brings low pH seawater to the surface ocean (Feely and others 2008). Although this upwelling is a natural phenomenon in this region, the ocean uptake of anthropogenic CO_2 has increased the extent of the affected area. In response to an observed association between lower seawater pH/aragonite saturation and oyster larvae die-off,[15] hatcheries and oyster-growing facilities along the West Coast of the U.S. have begun to monitor the pH of the seawater pumped into their tanks and switch the pumps off when pH goes below a certain threshold. The production then relies on a closed seawater system, usually for a few hours as the upwelling effect is tidally regulated (B. Dewey pers. comm.; Barton and others 2012). A Willapa Bay-based oyster grower even opened a hatchery in Hawaii, rather than relying on local larvae. This may be one of the first businesses to migrate in response to ocean acidification.[16]

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[15] Whether this is due to acidification or not is still subject to debate. Ruesink and others (2012) conducted a re-analysis of the historical data that suggests these kinds of failures happen even in the absence of anthropogenic acidification. What matters here is that the phenomenon observed matches what can be expected to happen more frequently with on-going acidification: therefore, the example remains valid in any case to show what specific human groups can do to adapt.

[16] http://oceanacidification.wordpress.com/2012/06/22/willapa-bay-oyster-grower-sounds-alarm-starts-hatchery-in-hawaii/ Accessed 18 July 2012.

The oyster example shows that certain coastal industries have high potential to adapt to ocean acidification, at least within a narrow range of pH variation, but it is difficult to assess adaptation's potential more generally without further examples from which to draw conclusions. In general terms, there is a lot to be learnt from 20 years of climate change adaptation research and practice, especially on the limits of and barriers to adaptation. Limits are 'the conditions or factors that render adaptation ineffective as a response to climate change and are largely insurmountable' (Adger and others 2007). These limits will be closely linked to the rate and magnitude of ocean acidification, as well as associated key vulnerabilities. They will be met when entire ecosystems and life cycles are disrupted beyond a critical threshold. Hoegh-Guldberg and others (2007) for instance find that consequences on coral reefs become unmanageable for $[CO_2]_{atm}$ above 500 ppm: any coral-related human activity is then at risk and adapting to reduce impacts cannot succeed. There is, however, an ongoing debate over the very existence of social limits to successful climate change adaptation (Adger and others 2009).

Identifying barriers to acidification adaptation can also be grounded in the climate change literature—although potential specificities of acidification adaptation have not been discussed yet. Typical barriers to climate change adaptation (which likely apply to acidification as well) include financial constraints, information, cognitive, social and cultural barriers (Adger and others 2007). For instance, the difficulties in anticipating a complex, long-term risk when concrete, daily problems are numerous, the challenges of collective action (Olson 1965), or the need for reliable data and models at the appropriate scale (e.g. continuous, local pH monitoring) are likely to be crucial barriers to adaptation to ocean acidification as they are for climate change. At an individual level, Lorenzoni and others (2007) observed that despite widespread awareness and concern about climate change in the UK, personal engagement in climate action remains very marginal for reasons that are likely relevant to ocean acidification—including lack of knowledge about where to find information, perceived information overload, and information not being accessible to non-experts. Given ocean acidification's much lower public profile than climate change (hence, 'the other CO_2 problem'), we might add to this list a more pervasive lack of public awareness as a primary hurdle to individual action.

The climate change adaptation track record (see e.g. Berrang-Ford and others 2011) indicates that opportunities for ocean acidification adaptation are likely to be abundant as the issue percolates to the political agenda. Climate change adaptation policies, strategies and projects have indeed proliferated as political attention was growing and funding available was quickly increasing. The question is rather whether such opportunities may actually stimulate timely and effective adaptation, which is far from the rule in the climate change context (Repetto 2008; Garnaud and Billé 2010).

Repairing Damages When the Ocean has Already Acidified

Reducing Acidity Using Additives Other Than Iron

The addition of powdered alkaline rocks such as calcium carbonate ('liming') has been used to counteract lake acidification for many years (Weatherley 1988). Similar ocean-based techniques aim at accelerating the natural process of rock weathering that supplies alkaline substances through rivers and runoff. These approaches increase the alkalinity of seawater through the addition of calcium oxide (Kheshgi 1995), addition of the products of the dissolution of limestone (calcium and bicarbonate; Rau and others, 2007), or open water dissolution of fine-grained olivine (Köhler and others 2010).

There is limited experimental evidence that alkalinisation could be useful in coastal environments such as mud flats (Green and others 2009). The survival of juveniles of the commercial clam *Mercenaria mercenaria* decreases as a function of decreasing pH and $CaCO_3$ saturation state in the clams' sediment habitat. One experiment manipulated the sediment saturation state by adding crushed bivalve shells to a mud flat in West Bath, Maine, U.S.A., finding that the numbers of live clams in buffered sediment increased almost three-fold relative to controls in only two weeks (Green and others 2009). Such small-scale sediment buffering may be a potentially important management strategy to decrease dissolution mortality in coastal environments.

Chemical buffering seems unlikely to scale up, however. Global models suggest that ocean alkalinisation has the potential to mitigate atmospheric CO_2 and ocean acidification but requires large-scale, long-term, 'alkalinity intensive' additions (Ilyina pers. comm.). The cost of the addition of limestone products ranges from US\$38 to US\$74 per ton of CO_2 mitigated, which is close or below the higher end of the cost of conventional carbon capture and geological storage (Rau 2008, 2011). However, this estimate does not take into account the CO_2 footprint of these additions related to mining, transport or delivery, which may well outweigh the expected benefit of liming. Much work remains to be done on the biogeochemical and ecological impacts of the chemical additions, costing (including a better estimate of the cost of transportation and damages due to the generation of dust) as well as on the development of methods for verification and monitoring (The Royal Society 2009).

Restoring Degraded Ecosystems

A potential response to the threat of ocean acidification is to use opportunities for ecological restoration, going beyond the current focus on restoring species, populations or habitat condition, to approaches that anticipate future ocean acidification. Estuaries provide such an opportunity because they are local hot spots of acidification (Doney 2010; Feely and others 2010; Kelly and others 2011) in which substantial economies are reliant on healthy functioning ecosystems. Estuaries have been acidifying for decades due to nutrient enrichment (resulting in organic carbon decomposition), changes in river flows with greater freshwater input reducing buffering rates (Salisbury and others 2008; Najjar and others 2010), and inputs of other 'acidifying' chemicals from the air and run-off, such as nitrogen and sulphur (Gypens and others 2009; Doney 2010; Waldbusser and others 2011b). Due to rapid rates of acidification in estuaries, shellfish industries are already experiencing increased mortality of larval and juvenile oysters (Green and others 2009; Talmage and Gobler 2010; Barton and others 2012), which has forged new collaborations between scientists, conservation groups and industry.

Ecological restoration projects undertaken by global conservation bodies such as The Nature Conservancy already employ strategies of placing cultch to speed up recovery of previously depleted shellfish beds (Beck and others 2009, 2011). Management strategies that promote oyster reef recovery in estuaries by returning old shells back to the extraction point could also buffer the impacts of acidification (Green and others 2009; Waldbusser and others 2011a) while increasing natural larval settlement and providing habitat for other species. This approach would increase pore water calcium carbonate saturation state thus reducing dissolution risk. Even a very small survivorship benefit at the settlement stage would translate to large increases in harvestable, adult population and could form a vital part of future coping strategies. Whether the provision of cultch provides a stimulus for increased recruitment in its own right, or whether this is dependent on improved local geochemical conditions, is still unknown. In any case, there is ample opportunity to form new alliances between industries and conservation sectors to achieve mutually beneficial results.

In addition, modelling and monitoring of coral reef environments has highlighted the potential for the algae and/or seaweeds to draw down the total carbon in the water column through photosynthesis and actually ameliorate the process of acidification at a local scale (Anthony and others 2011a; Kleypas and others 2011). Thus, coral reef communities could potentially benefit from healthy seaweed populations depending on the water circulation patterns. The same amelioration of acidification is expected for patch reefs surrounded by healthy seagrass beds (Manzello and others 2012). The carbonate chemistry surrounding small patch reefs in seagrass beds along the Florida Reef Tract can currently experience carbonate chemistry conditions that were common during the pre-industrial era (Manzello and others 2012). Thus, restoration of seagrass or algal beds surrounding coral reefs could be considered as a tool to combat ocean acidification's impacts at a local scale, although the utility of this approach will be dependent on the depth of the reefs, the scale of the beds, and the water circulation patterns and residence times.

It has also been proposed that selectively bred lines of acidification-tolerant strains of target species be used in restoration efforts (Rau and others 2012). For example, lines of the Sydney Rock Oyster bred for aquaculture have been shown to fare better when exposed to acidification stress than the individuals from the native population (Parker and others 2011), and could enhance the effectiveness of oyster restoration in light of the threat of ocean acidification. However, the feasibility and unforeseen consequences of introducing novel genotypes remain a major concern. While several other more active approaches to restoration (or conservation) have also been proposed (Rau and others 2012; McLeod and others 2013), little is known about the utility of these approaches and research is badly needed to address their effectiveness and potential drawbacks.

Discussion

Weighing Potential Actions Against Ocean Acidification

Our attempt at a comprehensive review of options to take action against ocean acidification reveals that not all of the available alternatives are equally effective or feasible. They also interact, and, therefore, they are not to be considered independently but as a bundle. For instance: building ecosystem resilience will be all the more efficient as acidification is limited; locally reducing acidity could become a regular management measure for MPAs; local action against coastal acidification could stimulate more ambitious efforts on CO_2; having techniques available to manage solar radiation may be a disincentive to cut GHG emissions, including CO_2.

Any of the alternatives discussed here merely buys time to reduce CO_2 emissions, which remains vital whatever other action is taken. The first key question is, therefore, whether and how ocean acidification can make a difference in the complex and difficult UNFCCC talks. Incorporating ocean acidification into the negotiations would aim both at encouraging drastic CO_2 emissions reductions and at ensuring that mitigation policies take non-thermal effects of CO_2 into account—hence differentiating CO_2 from other GHGs. We can speculate that ocean acidification might be able to provide additional urgency to act, as the chemical understanding is clear and impacts are very likely irreversible on a human timescale. Cooley and Doney (2009) and a 2010 United Nations Environment Programme report (Turley and Boot 2010) both demonstrate the vulnerability of ocean protein sources for various nations. Ciurak (2012) even reports that ocean acidification impacts on the Great Barrier Reef were decisive in the adoption of a carbon tax in Australia. At the same time, that some island States may disappear, that densely populated deltas and low-lying coastal areas will suffer ever more extreme climate events, or that desertification will drive hundreds million people towards food insecurity, have so far been insufficient arguments for the international community to take appropriate coordinated action on GHG emissions. There are, therefore, few reasons to be optimistic that ocean acidification will fare better as an argument. Finally, the highly uncertain future of carbon markets and global commitments to reduce emissions means that the equivalence issue between CO_2 and other GHGs may not prove decisive.

No geoengineering method appears to provide an easy or readily acceptable alternative solution to ocean acidification, in contrast to low-carbon technologies (Joos and others 2011). However, methods to remove CO_2 from the atmosphere may become a necessity in light of the present trajectory of CO_2 emissions (Rau and others 2012). CO_2 removal involves fewer uncertainties and risks than solar radiation management techniques, and is much more effective against acidification. In the same vein, reducing non-CO_2 GHG emissions will not make a big difference in the short to medium term as far as global acidification is concerned, but it may prove opportune in the long term to prevent release of methane hydrates and acidification in specific areas. Hence even small steps, such as relatively easy non-CO_2 GHG emissions reductions (e.g. HFC), might be of long-term benefit to ocean ecosystems.

Reducing coastal pollution sources is important for many reasons other than acidification, ranging from public health to ecosystem structure and function. However—and probably more efficiently than in the case of the global climate talks—acidification can stimulate more effective and ambitious action towards local pollution reduction, as it has in Washington, USA. It can help build new strategic alliances with powerful stakeholders like the fisheries and shellfish industries. To this end, a spatially explicit evaluation of the relative importance of different causes of acidification is necessary to maximize the utility of smaller-scale policy recommendations.

Strengthening ecosystems resilience and restoring the ones that have suffered from ocean acidification should be another cornerstone of action. The benefits of such action are plenty: these techniques address many stressors simultaneously; much can be done within single jurisdictions, thus minimizing transaction costs; and many years of research have generated extensive experience in conservation and restoration. The 10th Conference of the Parties to the Convention on Biological Diversity (CBD COP 10) adopted as a target that by 2020 10 % of coastal and marine areas should be protected. The target created a new impetus for MPAs and the area protected is now fast increasing worldwide, although still below 2 % (Bertzky 2012). In addition, it appears that easy and low-tech actions like returning crushed shell material to coastal habitats can in some cases substantially increase pH and mitigate localized acidification impacts.

Finally, it should be noted that scale issues are fundamental. Frequently the same practice or behaviour that is a local and immediate problem is also a global, long-term issue: for instance, agricultural intensification generates local pollutions contributing to local acidification while N_2O from fertilisers is a major global GHG. Local and global efforts target essentially the same sectors (agriculture, waste, energy and transport), but responses at one scale may be counterproductive at another. In the case of air pollution, for example, the catalytic converter solves a local pollution problem associated with exhaust systems, but reduces the efficiency of combustion, thereby increasing global CO_2 emissions. A more holistic option—and one that would work across scales—would rather be to reduce fossil fuel-powered transportation altogether, by investing in public transit or other low-carbon transport options. Such scale-independent, holistic policies are preferable, and our review shows there are many in the context of ocean acidification.

In an attempt to synthesize the discussion, Fig. 1 qualitatively compares the various options discussed. ‘Potential’ refers to how effective each option may be with regard to fighting ocean acidification, and ‘feasibility’ is understood as reflecting the ratio between the technological, political, and economic opportunities and barriers we have reviewed above. This diagram is intended to be heuristic, rather than a formal accounting; what is important is the relative position of options along the two axes. Four clusters arise:

1. The two options targeting CO_2 concentration in the atmosphere clearly have the greatest potential, and cannot be compared with others—at least not on the same scale. The political and social feasibility of immediate reductions in CO_2 emissions raises concerns while technology is largely available: depending on the viewpoint, feasibility can hence be considered relatively low or high. CO_2 removal may be politically

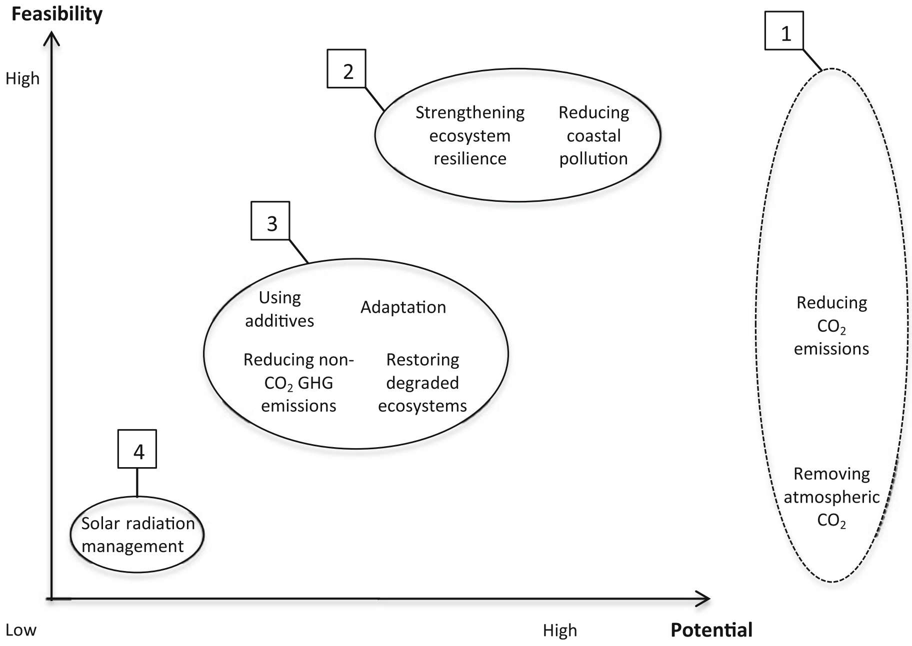

Fig. 1 Comparing potential and feasibility of options

easier but there are high uncertainties regarding technologies as no large-scale demonstration has been undertaken.

2. Strengthening ecosystem resilience and reducing coastal pollution have both high potential and feasibility. They are no-regret strategies (i.e. justified under all plausible future scenarios) and offer massive co-benefits: they are probably the two options offering the greatest combination of political and biochemical advantage as of today.
3. Then comes a cluster of four options (adapting, restoring degraded ecosystems, using additives and reducing non-CO_2 GHG emissions) that have a lower potential than clusters 1 and 2, and rank somewhere in the middle in terms of feasibility. They still deserve significant attention either because they are effective in the short term or because they have important co-benefits. Their respective potential and feasibility cannot be compared with the current state of knowledge.
4. Finally, solar radiation management appears to be of little potential with respect to counteracting ocean acidification in the short-to-medium term, although reducing warming via radiation management may be more relevant at timescales of a few centuries, depending upon the projected risk of methane hydrate dissolution.

Legal and Political Basis for Action

The review of options to combat ocean acidification raises the question of whether new legal instruments (multilateral environmental agreements such as conventions and protocols, or domestic statutes) are needed, or whether the legal basis for action already exists while policies (i.e. implementation efforts) are the limit. The answer appears to be the latter: although it is a recently emerged global environmental concern, ocean acidification does not require significant changes in existing legal frameworks. Reducing CO_2 and other GHG emissions, reducing local nutrient pollutions, protecting and restoring ecosystems, adapting human activities or introducing additives: the frameworks to take action are already in place to a large extent at the global, regional, national and local levels. What is lacking is implementation.

At the global level, GHG emissions are handled under the UNFCCC, one objective of which is to achieve 'stabilization of greenhouse gas concentrations in the atmosphere at a low enough level to prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change[17]'. Despite ocean acidification not being an animating concern of the UNFCCC, the Convention provides a key forum for addressing CO_2 emissions (Harrould-Kolieb and Herr 2011), the primary cause of both climate change and ocean acidification. However, the national-level implementation of UNFCCC commitments has so far left much to be desired, as shown by still-climbing atmospheric CO_2. A binding, global and ambitious agreement on GHG emissions after 2015 is vital. Nevertheless a global temperature

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[17] Article 2.

target, such as the 2 °C limit, can only partly address the Article 2 objective. This objective may require multiple targets, including on ocean acidification. Steinacher and others (2013) quantified allowable carbon emissions for multiple targets and provided probabilistic information regarding whether a target set, i.e. the combination of specific global and regional targets, will be met. For a given likelihood to respect a selected target set the allowable cumulative emissions are reduced significantly from those inferred from the temperature target alone.

Besides the UNFCCC, CO_2 uptake by the ocean, either from the atmosphere or dissolved methane hydrates, easily fits the definition of marine pollution in Article 1 of the UNCLOS: 'the introduction by man, directly or indirectly, of substances or energy into the marine environment (…) which results or is likely to result in such deleterious effects as harm to living resources and marine life.' CBD COP 10 made ample reference to ocean acidification (CBD Secretariat 2010), and several of the CBD 2020 Aichi targets are also relevant to acidification, such as target 8 (coastal pollution including excess nutrients), target 10 (stresses to coral reefs including ocean acidification) and target 15 (conservation and restoration of ecosystems to increase resilience). Whether these crucial international objectives will be met is, again, a matter of designing and implementing appropriate policies at the domestic level, as this is where actual policy implementation takes place.

As to regulating CO_2 removal methods, the international legal framework seems sufficient for most techniques: OIF e.g. is regulated by a resolution[18] adopted in 2008 under the London Convention and Protocol in which Contracting Parties declared that given the present state of knowledge, ocean fertilisation activities other than legitimate scientific research should not be allowed. Two CBD decisions from 2008 to 2010 go in the same direction. Solar radiation management is not covered by any international governance framework, but for reasons discussed above, it remains marginal in the ocean acidification debate.

One notable international regulatory gap does exist. MPAs could be a key tool in reducing anthropogenic stressors on discrete areas of special concern, perhaps improving the ability of those systems to better withstand acidification. However, no global legal framework yet exists to establish MPAs in areas beyond national jurisdiction (Druel 2011), and the limits faced by regional efforts, e.g. in the North-East Atlantic, are evidence of the difficulty of proceeding without a firm basis in such a global legal instrument (Druel and others 2012).

The regional level has seen the development of many legal instruments and policies to fight land-based pollutions over the past decades (Rochette and Chabason 2011). For example, the European Union adopted the Water Framework Directive (2000) and the EU Marine Strategy Framework Directive (2008), and specific protocols were adopted within several UNEP regional seas frameworks: among others the Barcelona Convention in 1980, or the Nairobi Convention in 2010. Yet such protocols have received relatively little political attention (Rochette and Billé 2013) and whether they can inspire long-term improvement in pollution reduction remains to be seen.

At the national level, a systematic review is beyond the scope of the present paper, but we can illustrate a number of applicable legal instruments with the U.S. example. The U.S., who ratified the UNFCCC but are not Party to the UNCLOS and CBD, are relatively well equipped to contribute to combat acidification. The Federal Ocean Acidification Research and Monitoring Act, signed by President Obama in 2009, established a research programme within the National Oceanic and Atmospheric Administration and provided funding for research. The Clean Air Act, perhaps surprisingly, allows the U.S. to regulate CO_2 as a pollutant, and the Act has been used in minor ways to reduce emissions from automobiles and major new sources of pollution. Meanwhile, the Clean Water Act regulates marine pH explicitly, providing a potentially powerful tool for combating ocean acidification (Kelly and Caldwell 2013).

Finally, at the local and subnational levels, still with the U.S. example, Kelly and Caldwell (2012) note that states and local jurisdictions often have the legal authority to control coastal pollutants that may make those habitats more vulnerable to acidification.

A fundamental characteristic of the ocean acidification issue is, therefore, the current discrepancy between essentially appropriate legal frameworks at all scales, with few exceptions, and insufficient or inefficient policies to translate them into action.

Conclusion

The objective of this paper was to review management options and related policy frameworks in a systematic, international and critical way. We investigated the assumption that fighting acidification is mainly, but not only about reducing CO_2 emissions, and explored the leeway that this emerging issue may open in older environmental issues. Based on the best available science, we reviewed nine types of responses, initially grouped under four categories. Connecting and comparing them leads to identifying four new clusters: (1) an ideal one, of high potential but facing great barriers for implementation; a cluster of 'false solutions' (4) which our review finds of little potential and hardly feasible; and two clusters (2 and 3) of options that offer partial (though noteworthy)

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[18] LC-LP.1 (2008).

solutions to buy time while we struggle to limit the concentration of atmospheric CO_2. Finally, a key pattern of ocean acidification appears to be the striking discrepancy between largely appropriate legal frameworks at all scales—ranging from the UNFCCC at the international level, all the way down to the authority of cities and other local governments to reduce their own air and water pollution—and inadequate policies to reach objectives that are broadly agreed-upon. We believe that beyond more effective implementation, better and enhanced coordination between relevant international frameworks is key, but we do not concur with Kim (2012) that a new multilateral environmental agreement on ocean acidification is needed.

A number of handicaps will undoubtedly hamper action against ocean acidification in the near future. Three of these handicaps stem from the nature of acidification's socio-economic and biological impacts: (i) these impacts are still poorly defined and hardly quantified. Impact science is in its infancy although fast progressing; (ii) they are largely 'invisible', both because they are difficult to isolate from those for other stressors, and because they occur underwater (contrary e.g. to acid rain on forests); (iii) ocean acidification is a global issue (i.e. it is happening in the entire ocean and needs to be addressed globally) but will impact societies and ecosystems very unevenly and with different time scales. As a result, the motivation to take action will be uneven as well. Another handicap of a different nature is that most options reviewed here have already been identified in the context of other environmental problems; one must admit that we have not been very successful in implementing them with adequate intensity at the appropriate scale—beyond the many circumscribed success stories.

These are all reasons why one should not expect an easy solution to ocean acidification. The foregoing means that effective acidification policy requires that we succeed where we failed to a large extent so far: reducing CO_2 emissions, protecting marine ecosystems from various stressors, restoring the ones that have been degraded and developing last-resort technologies to cope in the worst-case scenario. Given the uncertain future outcome of CO_2 emissions reductions efforts, any action that can be taken will have to be, however marginal its effect may seem: thresholds (which we know little about) mean that a difference of 0.05 unit of pH or less can be significant even after a decrease of 0.3. Typically, coastal pollutions or even the release of methane hydrates can push some ecosystems beyond thresholds—and degraded ecosystems have lower acidity thresholds.

In any case, ocean acidification clearly is one more reason why a failure of climate change talks would risk leaving future generations an even more profoundly altered planet. Admittedly it is one in an already long list of incentives for action, but acidification also has aspects (rapid timescales, economic and social impacts, potential irreversibility) that may help make a difference. By better engaging in debates over energy, climate and pollution control, the ocean community could create a new suite of interested parties, which may tip the balance from acknowledgement to better-informed decision-making and action. What is true of climate talks is of other decision processes at all scales: ocean acidification offers opportunities to build new and sometimes unexpected strategic alliances with powerful partners from the private sector. Finally, let us keep in mind at all times that the worst-case scenario would be to create new problems while trying to fix ocean acidification: many of the options reviewed are no-regret and reversible, and they are the ones to favour.

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