The Honolulu Declaration on Ocean Acidification and Reef Management

Prepared and adopted by participants of the Ocean Acidification Workshop, convened by The Nature Conservancy, 12-14 August 2008, Hawaii

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Founded in 1948, The World Conservation Union brings together States, government agencies and a diverse range of non-governmental organizations in a unique world partnership: over 1000 members in all, spread across some 140 countries. As a Union, IUCN seeks to influence, encourage and assist societies throughout the world to conserve the integrity and diversity of nature and to ensure that any use of natural resources is equitable and ecologically sustainable.

The IUCN Global Marine Programme provides vital linkages for the Union and its members to all the IUCN activities that deal with marine issues, including projects and initiatives of the Regional offices and the 6 IUCN Commissions. The IUCN Global Marine Programme works on issues such as integrated coastal and marine management, fisheries, marine protected areas, large marine ecosystems, coral reefs, marine invasives and protection of high and deep seas.

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The mission of The Nature Conservancy is to preserve the plants, animals and natural communities that represent the diversity of life on Earth by protecting the lands and waters they need to survive. The Conservancy launched the Global Marine Initiative in 2002 to protect and restore the most resilient examples of ocean and coastal ecosystems in ways that benefit marine life, local communities and economies. The Conservancy operates over 100 marine conservation projects in more than 21 countries and 22 U.S. states; we work with partners across seascapes and landscapes through transformative strategies and integrated planning and action. The focus is on: (1) Setting priorities for marine conservation using ecoregional assessments and tools for ecosystem based management; (2) Ensuring coral reef survival by creating resilient networks of marine protected areas; (3) Restoring and conserving coastal habitats by utilizing innovative new methods; (4) Building support for marine conservation through strategic partnerships and working to shape global and national policies. Marine conservation in The Nature Conservancy builds upon the organization’s core strengths: achieving demonstrable results; working with a wide range of partners, including nontraditional partners; science-based, robust conservation planning methodologies; our experience with transactions; and, perhaps most importantly, our ability and commitment to back up our strategies with human, financial and political capital. For more information e-mail marine@tnc.org or go to www.nature.org/marine.

The IUCN Resilience Science Working Group
The IUCN Resilience Science Working Group on coral bleaching, resilience, and climate change was established in 2006 by the Global Marine Programme of IUCN, The World Conservation Union, on a 3-year grant from the John D. and Catherine T. MacArthur Foundation. The goal of the working group is to draw on leading practitioners in coral reef science and management to streamline the identification and testing of management interventions to mitigate the impacts of climate change on coral reefs. The working group will consult and engage with experts in three key areas: climate change and coral bleaching research to incorporate the latest knowledge; management to identify key needs and capabilities on the ground; and ecological resilience to promote and develop the framework provided by resilience theory as a bridge between bleaching research and management implementation.

Acknowledgements
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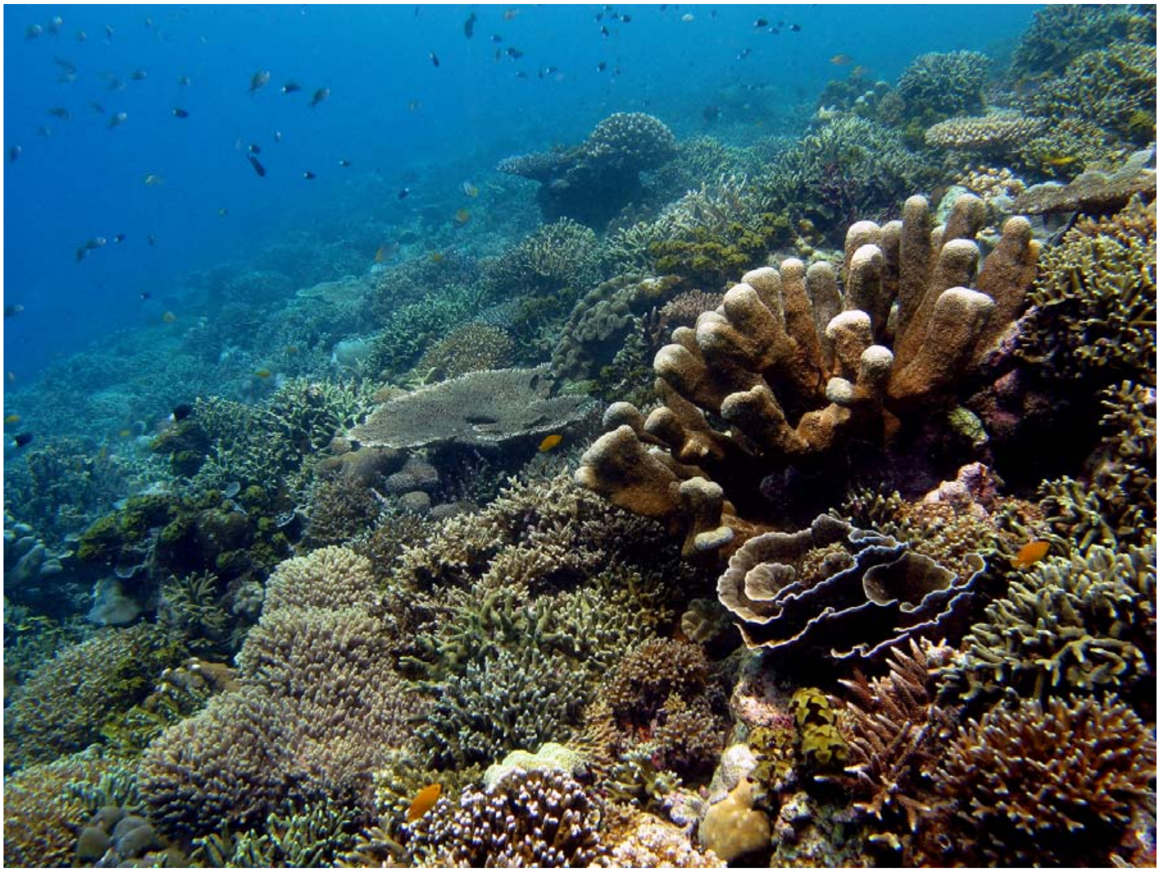


Resilient coral garden at Halmahera, Indonesia. Copyright: Emre Turak

Background

Ocean acidification is the change in ocean chemistry driven by the oceanic uptake of chemical inputs to the atmosphere, including carbon, nitrogen and sulfur compounds (Doney et al. 2007; Guinotte and Fabry 2008). The ocean absorbs about one-third of the carbon dioxide added to the atmosphere by human activities each year (Sabine et al. 2004); and the pH of the ocean surface waters has decreased by about 0.1 units since the beginning of the industrial revolution (Feely et al. 2004). If current carbon dioxide emission trends continue, the ocean will continue to undergo acidification, to an extent and at rates that have not occurred for tens of millions of years. A doubling of the concentration of atmospheric carbon dioxide, which could occur in as little as 50 years, could cause major changes in the marine environment, specifically impacting calcium carbonate organisms (Orr et al. 2005). Such changes compromise the long-term viability of coral reef ecosystems and the associated benefits that they provide.

Coral reefs systems provide economic and environmental services to millions of people as coastal protection from waves and storms, and as sources of food, pharmaceuticals, livelihoods, and revenues (Best and Bornbusch 2001). Coral reefs also support multi-billion dollar industries, such as tourism and fisheries. For example, in Hawaii, reef-related tourism and fishing generate $360 million per year, and their overall worth has been estimated at close to $10 billion (Cesar et al. 2002). Coral reefs and the services that they provide are threatened by the impacts of human stresses such as coastal development, pollution, overexploitation, and destructive fishing, in addition to climate change impacts.

Climate change impacts, specifically increases in sea temperature, sea level, and ocean acidity, jeopardize the biodiversity of the ocean and threaten the food security of dependent coastal communities. Scientific evidence suggests that by 2050, we may lose more coral reef area to erosion than can be rebuilt naturally if urgent steps are not taken to reduce atmospheric CO_2 (Hoegh-Guldberg et al. 2007). Scaled-up management actions on global emissions and on reef recovery are required if the loss of coral-dominated ecosystems is to be avoided.

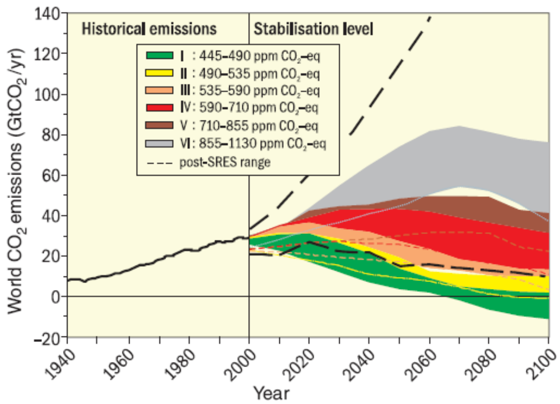
Recognizing the potential irreversibility of acidification impacts, it has never been more imperative to improve the management of coral reef ecosystems. The growing threat of climate change combined with escalating anthropogenic stressors on coral reefs requires a response that is both proactive and adaptive. To respond to this challenge, The Nature Conservancy convened a group of global ocean experts in Honolulu, Hawaii from August 12-14, 2008. The workshop participants included oceanographers, climate experts, marine scientists, and coral reef managers from around the world.

They identified two major strategies that must be implemented urgently and concurrently to mitigate the impacts of climate change and to safeguard the value of coral reef systems: 1) limit fossil fuel emissions; 2) build the resilience of tropical marine ecosystems and communities to maximize their ability to resist and recover from climate change impacts. Despite the dire predictions, there is hope for coral reefs if action is swift.

To enhance coral reef resilience to ocean acidification, the expert group agreed the following recommendations to adapt policy and management practices:

Policy Recommendations

1) The most logical and critical action to address the impacts of ocean acidification on coral reefs is to stabilize atmospheric carbon dioxide (CO_2) concentration. The currently high rates of coral bleaching indicate that at the present concentration (385 ppm), we have already passed temperature thresholds of most reef corals. The thresholds of ocean acidification range from the point where reduced skeletal growth affects a coral's ability to survive to the point where a reef loses the ability to maintain its structure. These thresholds will vary from coral to coral and from reef to reef. However, the best evidence to date suggests that skeletal growth of most corals will decrease by about 30% once atmospheric CO_2 concentration reaches 560 ppm (Langdon et al. 2000; Langdon and Atkinson 2005), and that many reefs will shift from a reef-growth to a reef-erosion state before that, particularly where reef-building corals have declined due to bleaching, disease and other factors.



Global CO_2 emissions for 1940 to 2000 and emissions ranges for categories of stabilization scenarios from 2000 to 2100. Colored shadings show stabilization scenarios grouped according to different targets (stabilization category I to VI). Black dashed lines give the emissions range of recent baseline scenarios published since the SRES (2000). (IPCC 2007)

2) Reduce land-based sources of pollution that contribute to lowering pH in coastal and ocean waters.

3) Reduce inputs of nitrogen and sulphur oxides and ammonium compounds that contribute to lowering pH in coastal and ocean waters.

4) Expand the content of ocean acidification in the Intergovernmental Panel on Climate Change 5th assessment report.

5) Increase appropriations internationally to support management responses commensurate with the global and increasing scope of the threat of ocean acidification.

6) Establish a coordinated international program on coral reef acidification to link academic institutions, NGOs, coral reef managers, and government agencies.
   - Build on existing structures and organizations (notably, IUCN networks, Micronesia Challenge, Caribbean Challenge, Coral Triangle Initiative, U.S. Coral Reef Task Force, Great Barrier Reef Marine Park Authority) as vehicles for increasing collaborations and partnerships

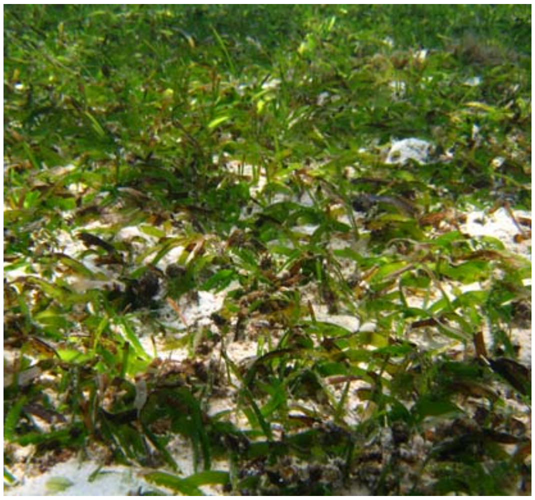
7) Mandate the inclusion of climate change actions (including those that address rising ocean acidification, sea level, and temperatures) into marine protected area (MPA) management plans as agencies routinely develop or revise their management plans.

Management Recommendations

8) Reduce all stresses on coral reefs as much as possible to enhance their health and resilience. Specifically, it is critical that management actions are taken to promote the ability of species, communities, and ecosystems to tolerate and recover from climate-change events, as well as local disturbances. This will enable key reef builders to focus their energy and resources on growth, calcification, and reproduction rather than on repairing damage and recovering from disease.

9) Identify and protect high biodiversity coral reefs that are likely to be less vulnerable to the impacts of ocean acidification, including
   a. high-diversity reef complexes that are well-flushed by oceanic water[1]
   b. reef complexes with dense seagrass beds and/or extensive reef flats with algal turfs[2]
   c. reefs in carbonate (especially magnesian-calcite) rich areas (such as those that include raised reefs and limestone islands, extensive reef flats, patch reef/coral head complexes, and carbonate sediment deposits)[3]

[1] Oceanic seawater usually has higher total alkalinity relative to lagoonal or poorly flushed waters, and consistently higher saturation states that support calcification
[2] Algal turfs and seagrasses are thought to benefit calcification because, during the sunlit hours when corals and coralline algae calcify the most, they photosynthesize and draw down carbon dioxide levels from the water column, and thus raise the saturation state
[3] Although dissolution rates of carbonate sediments are thought to be too slow to widely buffer seawater chemistry within most reef environments, the extent of buffering from carbonate-dominated substrates is almost certainly higher than in silicate-dominated substrates.



Dense seagrass bed in Wakatobi, Indonesia
Copyright: Elizabeth Mcleod

Rock Islands of Palau (limestone)
Copyright: Jez O'Hare

10) Spread the risk of ocean acidification by identifying and protecting at least three widely separated representative examples of each major coral reef community and major habitat type (includes known or likely high and low pH areas).

11) Adapt the design and management of MPAs to address ocean acidification impacts as follows:
    a. Incorporate reefs of low vulnerability or susceptibility to ocean acidification into MPA zoning plans during development or routine review, particularly those that include attributes listed in 9 a-c above
    b. Incorporate into MPA management plans specific adaptation strategies and actions to address climate-change threats (ocean acidification and warming and sea-level rise), including monitoring of their effectiveness
    c. Regularly review coral reef management plans to incorporate the latest research and scientific findings into a proactive and adaptive approach to address ocean acidification impacts
    d. Develop, test, and, where appropriate, apply interventions to reduce the effects of ocean acidification on high-priority areas and species, for example by reducing impacts from local disturbances
    e. Develop, test, and implement innovative interventions to reduce damage to reefs weakened by ocean acidification, and to promote the replenishment of reef communities impoverished by loss of coral species to the combined impacts of climate change, including elevated seawater temperatures and sea-level rise
    f. Integrate coral reef management with land-use and coastal zone planning and practices to reduce pollutant inputs (notably, ammonium compounds, nitrogen and sulphur oxides) that increase the acidity of local waters

12) Develop a coordinated international network of monitoring stations to map the vulnerability of coastal areas to ocean acidification at scales relevant to managers (20 – 30 strategically placed sites).

Monitoring buoy collects data on salinity, pCO_2 of air and water, temperature, and O_2 of air and water
Copyright: NOAA

13) Integrate acidification data into existing accessible data management systems (Coral Reef Watch, Carbon Dioxide Information Analysis Center).

14) Develop educational and informational materials to communicate the implications of ocean acidification for reef ecosystems and dependent communities emphasizing response actions.

15) Integrate the threat of ocean acidification into existing and new climate change programs and assessments

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APPENDIX A

Background text to support policy recommendations

Both policy and management actions are needed to address OA. Policies provide mechanisms to control CO2 emissions through local actions and global collaborations. Policies also provide the enabling framework for building adaptation responses to OA into coral reef management programs.

1) *The most logical and critical action to address the impacts of ocean acidification on coral reefs is to stabilize atmospheric carbon dioxide (CO_2) concentration. The currently high rates of coral bleaching indicate that at the present concentration (385 ppm), we have already passed temperature thresholds of most reef corals. The thresholds of ocean acidification range from the point where reduced skeletal growth affects a coral's ability to survive to the point where a reef loses the ability to maintain its structure. These thresholds will vary from coral to coral and from reef to reef. However, the best evidence to date suggests that skeletal growth of most corals will decrease by about 30% once atmospheric CO_2 concentration reaches 560 ppm (Langdon et al. 2000; Langdon and Atkinson 2005), and that many reefs will shift from a reef-growth to a reef-erosion state before that, particularly where reef-building corals have declined due to bleaching, disease and other factors.*

Ocean acidification is largely an invisible, creeping environmental problem. It is also a very recently recognized issue so there is limited empirical data on which to base the identification of exact thresholds. These thresholds could relate to the organism level (at what point is an organisms ability to survive or function exceeded?), the community level (at what point will a phase shift occur, say from a coral-dominated community to an algal-dominated community?), or the reef level (at what point will reef building cease and reef erosion begin?).

The effects of ocean acidification on the ability of reef organisms to calcify (that is, to build their skeletons or shells) have been the best-studied aspect of ocean acidification. A synthesis of these studies indicates that once atmospheric CO_2 levels reach 560 ppm (double the preindustrial level), calcification rates in corals and coralline algae will decrease from 5-60%, with most studies indicating about a 30% decrease (Langdon et al. 2000; Langdon and Atkinson 2005; Kleypas et al. 2006).

The potential for ocean acidification to cause phase shifts on coral reefs has not been explicitly studied, but a recent study conducted near a natural submarine CO_2 vent in the Mediterranean confirmed that carbonate-dominated systems are likely to shift to non-carbonate systems if they are subjected to ocean acidification (Hall-Spencer et al. 2008). At a pH of 7.8-7.9, the normal community included many calcareous organisms such as corals, sea urchins and coralline algae, that were absent or greatly reduced near the vent, where seagrasses and other algal species flourished. By comparison, the pH of average tropical waters was about 8.16 before the Industrial Revolution, and will be about 7.91 when atmospheric CO_2 levels reach 560 ppm.

Finally, the effects of ocean acidification on reef structures concerns the balance of calcium carbonate production by organisms and its removal by erosive forces. A reef exists simply because the coral community produces more calcium carbonate than is removed. Ocean acidification not only causes a reduction in calcification rates, it causes an increase in carbonate dissolution rates, so as ocean acidification proceeds, the net production of calcium carbonate will decrease. Reefs near the margins of reef development (e.g., high latitude reefs) are already near the limit of reef development and are likely to be the first to shift into an erosional state – some may already have done so. Reefs that are currently fast-growing, such as those in the warmest and clearest waters, are likely to be the last to shift to an erosional state. However, these predictions are greatly dependent on the overall health of the coral community. Coral communities with high coral cover and active coral growth will maintain a reef structure for much longer than those with greatly reduced live coral cover. The Galápagos reefs, for example, eroded away within a decade following the near total mortality of corals during the 1982-83 bleaching event (Manzello et al. 2008).

2) *Reduce land-based sources of pollution that contribute to lowering pH in coastal and ocean waters.*

Primary sources of nutrients and organic carbon into marine systems include agriculture (both extensive planting of nitrogen-fixing crops and the use of fertilizers), aquaculture, animal husbandry, and sewage. Nitrogen from animal and agricultural waste may leach from the soil as nitrate and flow to the ocean via rivers, streams, or groundwater, or it may volatilize as ammonia into the atmosphere, whence it may later be redeposited on land or at sea. The influx of nutrients to coastal environments may be limited by requiring that human and animal waste be treated to remove nutrients before discharge and minimizing the use of synthetic fertilizers in agriculture.

The production and remineralization of organic carbon in water and sediments can have a strong effect on saturation state and pH, particularly in coastal waters (Doney et al. 2007). These processes in turn are heavily influenced by atmospheric or riverine input of nutrients, primarily nitrogen and phosphorus, as well as the direct input of organic carbon. Nutrient input generally stimulates elevated primary production, which in turn supports increased populations of consumers. The decomposition and remineralization of the organic material releases CO_2, which in turn decreases the pH and saturation state of the water in which the processes occur (e.g., Andersson et al. 2006 and refs therein). Although some nitrogen enters the ocean as ammonia (NH_3), a strong base, in surface ocean water almost all ammonia is typically rapidly nitrified to NO_3 (nitrate), an acid (Doney et al. 2007). De la Paz et al. (2002) investigated the driving forces for temporal variability in CO_2 flux in tidal creeks in Spain, and determined that on seasonal scales periods of low pH were linked to seasonal changes in discharge from fish farms along the creek and increases in organic matter. Some models suggest that in the future input of nutrients and organic carbon may become the controlling factor for carbonate dissolution in marine water (Andersson et al. 2006).

3) *Reduce inputs of nitrogen and sulphur oxides and ammonium compounds that contribute to lowering pH in coastal and ocean waters.*

Fossil fuel combustion and agriculture practices over the past two centuries have resulted in increased inputs of nitrogen oxides (NO_x), ammonia (NH_3) and sulfur dioxide to the atmosphere (Doney et al. 2007). Much of this human-derived nitrogen and sulfur is deposited on the land and ocean surface as the dissociation products of nitric acid (HNO_3) and sulfuric acid (H_2SO_4). The largest fraction of this acid deposition occurs on land, in the coastal ocean, and in open ocean regions in the northern hemisphere. Consequently, the biological impacts of acid deposition are largest in lakes, streams, and coastal waters where the ecosystem responses could be significant.

4) *Expand the content of ocean acidification in the Intergovernmental Panel on Climate Change 5th assessment report*

The Intergovernmental Panel on Climate Change (IPCC) is a scientific intergovernmental body set up by the World Meteorological Organization (WMO) and by the United Nations Environment Programme (UNEP). The IPCC was established to provide decision-makers and others interested in climate change with an objective source of information about climate change. The main activity of the IPCC is to provide Assessment Reports of the state of knowledge on climate change.

The IPCC Assessment Reports become standard works of reference, widely used by policymakers, experts and students. The findings of the first IPCC Assessment Report of 1990 played a decisive role in catalyzing the United Nations Framework Convention on Climate Change (UNFCCC), which entered into force in 1994. The IPCC Second Assessment Report of 1995 provided key input for the negotiations of the Kyoto Protocol in 1997, the Third Assessment Report of 2001, and Special and Methodology Reports provided further information relevant for the development of the UNFCCC and the Kyoto Protocol. The IPCC continues to be a major source of information for the negotiations under the UNFCCC.

It is critical to expand the content of ocean acidification in the Fifth Assessment Report. Over the past 2-3 years, there has been an explosion of new research results on the biological consequences of ocean acidification in marine waters. This new information needs to be integrated into the next IPCC Assessment of the impacts of climate change on marine ecosystems and the potential consequences for humankind. Including more information on ocean acidification in the next Assessment report will help provide the necessary policy support for addressing the impacts of ocean acidification.

5) *Increase appropriations internationally to support management responses commensurate with the global and increasing scope of the threat of ocean acidification.*

Global funding for research and action related to the effects of ocean acidification and approaches to reducing acidification and its effects is grossly incommensurate with the severity of the issue. Foundations, governments, NGOs, and multilateral and bilateral funding agencies must all step up to the plate to make sure that effective mechanisms are in place to minimize the negative effects of ocean acidification before ocean ecosystems pass a point of no return. Funding must support both mitigation of fossil fuel emissions to address the cause of ocean acidification and adaptation measures that help build the resilience of marine ecosystems in the face of increasing acidification. There are direct actions that can be funded now to help boost coral reef resilience (see Management recommendations), and additional research is also needed to fill knowledge gaps and should be factored into donor programs and priorities.

The impacts of ocean acidification are not merely a concern for conservation-oriented funders. Because acidification also threatens marine-based food resources, development and anti-poverty funders should take action as well. For instance, such groups might fund projects geared towards increasing agricultural productivity while limiting the use of artificial fertilizers, or establishing cogeneration plants where methane is captured from municipal or animal waste. Ocean acidification should be explicitly included as a requirement in all funding proposals and other opportunities geared towards addressing climate change impacts in marine environments. Because adequately measuring water chemistry parameters relevant to ocean acidification is more expensive than measuring many other physiochemical parameters, governments currently funding ocean monitoring should consider appropriating extra funds to support the monitoring needed to understand the extent and dynamics of ocean acidification. Likewise, organizations and consortia engaged in ocean monitoring should consider raising extra funds to include parameters relevant to measuring ocean acidification.

6) *Establish a coordinated international program on coral reef acidification to link academic institutions, NGOs, coral reef managers, and government agencies.*
    - *Build on existing structures and organizations (notably, IUCN networks, Micronesia Challenge, Caribbean Challenge, Coral Triangle Initiative, U.S. Coral Reef Task Force, Great Barrier Reef Marine Park Authority) as vehicles for increasing collaborations and partnerships*

Several existing international and regional programs address aspects of climate change and offer the opportunity to share knowledge across vast geographic areas. However, networking among these programs and across organizations and scientific and management disciples has yet to be developed. UN agencies and IUCN[4] have global networks that represent all of these interest groups and provide the opportunity to develop and service such a multi-disciplinary global network.

7) *Mandate the inclusion of climate change actions (including those that address rising ocean acidification, sea level, and temperatures) into marine protected area (MPA) management plans as agencies routinely develop or revise their management plans.*

[4] IUCN is particularly suited to this role because its membership comprises governments, government agencies, NGOs, and research institutions.

Action must be taken to identify and initiate management responses to ocean acidification at national, state and local levels. Conservation authorities at all three levels periodically revise their management plans. As these management plans are revised under the authority of the various jurisdictions, Action Plans to address and respond to ocean acidification should be incorporated into the management planning process. These management planning processes should incorporate the best and most current science available, interpreting this into practical actions for implementation.

APPENDIX B

Background text to support management recommendations

The Honolulu Declaration lists a number of factors that could decrease the vulnerability of coral communities to ocean acidification. These provide the foundation for adaptation responses that conservation managers can implement to provide coral reefs facing ocean acidification with the best prognosis. Many of these strategies can be implemented immediately without major disruption to existing coral reef conservation programs and approaches. In particular, many of the resilience principles and approaches implemented to conserve coral reefs in the face of rising sea temperatures and mass bleaching (Salm et al. 2001; Salm and Coles 2001; West and Salm 2003; TNC 2004; Salm et al. 2006; Grimsditch and Salm 2006; Marshall and Schuttenberg 2006a; Marshall and Schuttenberg 2006b; McCook et al. 2007; Salm and McLeod 2007) apply equally to ocean acidification. By incorporating these principles as a matter of course into coral reef conservation programs, managers will enhance the resilience of reefs to the range of climate-change pressures, allowing time to plan and address adaptation needs specific to acidification.

The recommendations presented in the Honolulu Declaration are expanded upon below:

8) *Reduce all stresses on coral reefs as much as possible to enhance their health and resilience. Specifically, it is critical that management actions are taken to promote the ability of species, communities, and ecosystems to tolerate and recover from climate-change events, as well as local disturbances. This will enable key reef builders to focus their energy and resources on growth, calcification, and reproduction rather than on repairing damage and recovering from disease.*

Reducing local stresses will help corals cope with acidification. Similar to ocean warming, the effects of decreasing ocean pH are likely to be exacerbated by other stresses on coral reef organisms and processes. Therefore, ocean acidification further increases the already urgent imperative to control local stressors on coral reefs. Consequently, managers will need to increase control of all stressors, including water pollution, sedimentation and overfishing, to enhance the resilience of the coral reef ecosystems under their care.

9) *Identify and protect high biodiversity coral reefs that are likely to be less vulnerable to the impacts of ocean acidification, including*
    a. *high-diversity reef complexes that are well-flushed by oceanic water*

Reefs with high biodiversity have higher levels of functional redundancy (Nyström 2006). This means that key reef functions (such as herbivory or reef accretion) are more likely to be sustained even if individual species are lost. Because the role of different species in ecosystem resilience is not well known in many instances, the importance of biodiversity conservation is elevated as a goal for resilience-based management.

Consequently, managers should prioritize planning and conservation efforts toward reefs with high biodiversity where possible.

Well-flushed reefs may be less vulnerable to the impacts of ocean acidification. In most reef lagoons, the release of CO_2 via calcification exceeds the uptake of CO_2 via primary production. In reef lagoons with high residence times particularly, the CO_2 released by both decomposition of organic matter and calcification by corals, coralline algae, and other calcifying organisms accumulates and decreases the aragonite saturation state (Suzuki and Kawahata 1999). However, in some well-flushed lagoons, organic matter produced by photosynthesis is exported into the surrounding ocean so that it does not accumulate and decompose in the reef environment or contribute to raising the pCO_2 (Suzuki and Kawahata 1999). In addition, reefs that are well flushed by oceanic seawater, which usually has higher total alkalinity relative to lagoon or poorly-flushed waters, will be exposed to consistently higher aragonite saturation states that support calcification.

b. reef complexes with dense seagrass beds and/or extensive reef flats with algal turfs

Algal turfs and seagrasses are thought to benefit calcification because, during the sunlit hours when corals and coralline algae calcify the most, they photosynthesize and draw down carbon dioxide levels from the water column, and thus raise the saturation state. Seagrasses also have been shown to release organic acids through their roots into low nutrient carbonate sediments to dissolve the sediments and release phosphorus necessary for photosynthesis (Jensen et al. 1998). This enhanced dissolution process may elevate the alkalinity of overlying waters (Burdige et al. 2007) and provide some local buffering of the carbonate saturation state that will benefit corals and other calcifying organisms.

c. reefs in carbonate (especially magnesian-calcite) rich areas (such as those that include raised reefs and limestone islands, extensive reef flats, patch reef/coral head complexes, and carbonate sediment deposits)

Although dissolution rates of carbonate sediments are thought to be too slow to buffer seawater chemistry extensively within most reef environments, the extent of buffering from carbonate-dominated substrates is almost certainly higher than in silicate-dominated substrates. Primary productivity and coral reef calcification can have a large influence on the carbonate chemistry of seawater, particularly in lagoons, where the aragonite saturation state is lowered if seawater residence time is high (Suzuki et al. 2001; Suzuki and Kawahata 2004; Watanabe et al. 2006).

However, in some cases, high levels of evaporation in large shallow lagoons produce high-density water that sinks upon exiting through reef channels and cascades down the sheer reef faces. If such lagoons have extensive seagrass beds, they could function as open-ended systems, export organic matter and lose it to the depths. They thereby avoid the build up of CO_2 released by decomposition. The intriguing question for managers and researchers is: could such systems export sufficient high-alkalinity / low dissolved inorganic carbon waters over the surrounding reefs to counteract acidification locally?

10) *Spread the risk of ocean acidification by identifying and protecting at least three widely separated representative examples of each major coral reef community and major habitat type (includes known or likely high and low pH areas).*

An element of spreading risk must be built into MPA zoning and network design because (1) little if anything has been published regarding the resilience of corals to ocean acidification, (2) there are many uncertainties surrounding the response of coral reef communities to ocean acidification and other climate-change stressors, and (3) ocean acidification will likely not impact coral species equally everywhere. To spread the risk of losing one type of coral reef community or individual species to ocean acidification, managers should protect multiple examples of the full range of coral reef habitat and community types (Ballantine 1997; Salm et al. 2006) in a variety of conditions (e.g., high and low pH areas), and spread them out to minimize the chance that all will be wiped out by the same disturbance (McLeod et al. in press). Spreading risk combined with targeted monitoring is also important given our currently limited level of understanding regarding the relative importance of various factors in decreasing vulnerability to ocean acidification. This approach will allow managers to take immediate action, learn while doing, increase understanding, and refine their approaches as new knowledge develops.

11) *Adapt the design and management of MPAs to address ocean acidification impacts as follows:*
    a. *Incorporate reefs of low vulnerability or susceptibility to ocean acidification into MPA zoning plans during development or routine review, particularly those that include attributes listed in 9a-c above*

Through analyzing local environmental factors that contribute to coral community resistance and resilience to ocean acidification, managers can identify areas of greater tolerance and increased survival prospects. These communities can serve as refugia and provide coral colonies for local transplantation and restoration of damaged sites. Identifying these areas with certainty requires a better understanding of the factors that determine resilience, but all such efforts are likely to benefit conservation of coral reefs. Examples of factors that might confer resilience to acidification include presence of dense seagrass beds and other characteristics that could create favorable biochemical conditions.

Selecting reefs in a variety of pH and aragonite saturation regimes increases the chances of capturing corals that are hardened to a variety of pH conditions by the chemistry of their surroundings. It also spreads the risk of any coral species' survival being compromised by ocean acidification. Analyses of historical pH and aragonite saturation states where available and projections of these using climate models will yield patterns that may indicate reefs or coral communities within them that are likely to have higher or lower exposure to ocean acidification and, as a consequence, to be more or less vulnerable to altered pH and aragonite saturation states.

b. Incorporate into MPA management plans specific adaptation strategies and actions to address climate-change threats (ocean acidification, warming, and sea-level rise), including monitoring of their effectiveness

Marine Protected Areas (MPAs) have been identified as one of the most effective tools for conserving coral reefs and related marine systems (Kelleher 1999; Salm et al. 2000; Lubchenco et al. 2003; Palumbi 2003). However, it is recognized that protected area managers must incorporate climate change as well as the increasing pressures of human activities into the design and management of MPAs if they are to be effective in preserving the biodiversity and ecosystem values of coral reefs (Salm et al. 2006).

Current approaches to MPA selection are often inadequate to protect coral reefs from the effects of climate change (Graham et al. 2008), highlighting the need to adapt MPA planning and implementation to address climate change as a significant threat. Managers will need to include ocean acidification, along with other threats, into their management plans and develop specific strategies and actions to address its impacts on the coral reefs under their care.

c. Regularly review coral reef management plans to incorporate the latest research and scientific findings into a proactive and adaptive approach to address ocean acidification impacts

MPA management plans are prepared for fixed terms that commonly vary between two and 25 years. The longer term management plans generally call for review and course corrections every five years. The development of new management plans and review and revision of existing ones provide windows of opportunity for the consideration and incorporation of specific adaptation strategies and actions to address all climate-change threats (ocean acidification, warming, and sea-level rise).

d. Develop, test, and, where appropriate, apply interventions to reduce the effects of ocean acidification on high-priority areas and species, for example by reducing impacts from local disturbances

Weakened coral skeletons, slowed coral growth, and loss of sensitive coral species are all likely consequences of ocean acidification. These are problems that will challenge managers to produce innovative approaches to help ensure the persistence of ecosystem values and biodiversity on the priority reefs under their care. This is especially true for high-latitude reefs because of the greater solubility of CO_2 in colder water and lower aragonite saturation state. In addition to linking MPA management with coastal zone planning and design approaches, there are also local interventions that managers can make to help high-priority coral reefs and species cope with ocean acidification. Ultimately, managers will need to develop, test, and, where appropriate, apply interventions to reduce all synergistic impacts from local disturbances on high-priority areas and species.

e. *Develop, test, and implement innovative interventions to reduce damage to reefs weakened by ocean acidification, and to promote the replenishment of reef communities impoverished by loss of coral species to the combined impacts of climate change, including elevated seawater temperatures and sea-level rise*

MPA managers will need to develop and apply local-scale actions to reduce the damage of permitted activities on reefs weakened by ocean acidification, and to promote the replenishment of reef communities impoverished by loss of coral species to the combined impacts of climate change, including elevated seawater temperatures and sea-level rise. Approaches open to managers to reduce physical damage to weakened corals and reef structures are analogous to those practiced in sensitive terrestrial environments. They include restricting access to designated trails and less sensitive parts and restricting activities or use of equipment likely to impact sensitive communities and species.

It is likely that some sensitive coral species may succumb more rapidly to acidification, break apart, reduce rugosity, and leave gaps in the reef structure. In such cases, managers may need to consider replacement of these corals with more resistant species from the same reef complex to maintain reef structure.

f. *Integrate coral reef management with land-use and coastal zone planning and practices to reduce pollutant inputs (notably, ammonium compounds, nitrogen and sulphur oxides) that increase the acidity of local waters*

Integrated coastal zone management (ICZM) programs have the overarching goal of providing for multiple sustainable uses of natural resources, enhancing the welfare of coastal communities, and preserving biodiversity as well as protection against natural hazards, pollution from both land and sea, and other destructive extractive or development activities (Clark 1996). ICZM offers the mechanism to integrate land use planning and practice with coral reef management and control pollutants entering the near-shore marine environment.

Many pollutants that act to accelerate ocean acidification may originate inland, highlighting the need for integrated management that goes beyond the coastal zone. Links between land-based sources of pollution and pH of coastal waters reinforce the importance of ICZM for effective coral reef management. Particular pollutants of concern are nitrogen and sulfur oxides arising from fossil fuel burning, and ammonium compounds, nutrients, and organic carbon arising primarily from sewage, agriculture, aquaculture, and animal husbandry. Atmospheric deposition is the primary pathway for the input of nitrogen and sulfur oxides and ammonia into marine waters. These compounds rapidly undergo chemical reactions to produce acids that directly lower ocean pH, compounding the acidifying effect of CO_2. Nutrient and organic carbon input can decrease ocean pH by stimulating water-column productivity to levels that can deplete oxygen supply and consequently the rate of decomposition and remineralization of organic material, both of which release CO_2 into surrounding waters and lower pH. While some nutrient pollution occurs within the coastal zone, much is transported from far inland by river systems.

12) *Develop a coordinated international network of monitoring stations to map the vulnerability of coastal areas to ocean acidification at scales relevant to managers (20 – 30 strategically placed sites).*

The Coral Reef Monitoring Network (CRMN) would consist of 20 -30 regional autonomous observatories designed to characterize and monitor coral reef ecosystem performance. The CRMN would consist of autonomous moored systems designed to monitor the *in situ* metabolic activity (photosynthesis, respiration, and calcification) and carbonate chemistry of selected coral reef systems. These observing systems could also be complimented using survey cruises and remote sensing approaches to provide background data to verify models of community-scale metabolic performance which could serve as an important bio-indicators for identifying early ecological changes in response to chronic (e.g., ocean acidification) and acute (e.g., bleaching) stressors.

13) *Integrate acidification data into existing accessible data management systems (Coral Reef Watch, Carbon Dioxide Information Analysis Center).*

NOAA's Coral Reef Conservation Program is working jointly with other NOAA programs including NOAA's Coral Reef Watch, Pacific Islands Fisheries Science Center (PIFSC), Atlantic Oceanographic and Meteorological Laboratory (AOML), and Pacific Marine Environmental Laboratory (PMEL) to advance a NOAA-wide initiative on ocean acidification. They are also working with several university and federal partners including the University of Miami Rosenstiel School of Marine and Atmospheric Science (RSMAS) and the U.S. Geological Survey (USGS). The initiative seeks to provide NOAA and its stakeholder community with: 1) a comprehensive characterization of the ocean acidification threat to marine ecosystems; 2) the monitoring capacity to quantify and track ocean acidification and its impacts in oceanic and coastal systems; 3) an improved forecasting capability to provide stakeholders with the capacity to proactively respond to ocean acidification; and 4) adaptive management tools and requisite scientific knowledge for understanding and responding to ocean acidification in support of ecosystem-based management.

Specific Programs:

1. Develop a product suite of mapped fields for surface carbonate chemistry including saturation state for selected regions
    - The maps are derived using near-real- time satellite remote sensing and modeled environmental parameters to estimate changes in sea surface carbonate chemistry
    - The model is presently geared to the Greater Caribbean Region (GCR) but it will be extended to the remote Pacific
2. Establish a baseline for saturation state across the remote systems of the Line Islands
    - Ocean acidification changes will be tracked as part of a sustained repeat survey effort. NOAA's PIFSC, PMEL, and the Coral Reef Alliance (CORAL) are working together on this
    - Methods are similar to the GCR, but supplemented with near-reef observations

- Results will be used to evaluate which reef habitats will be most susceptible to ocean acidification and should be available in 2009

3. Establish methodologies for monitoring, assessing, and modeling the impacts of ocean acidification on coral reef ecosystems to help refine critical thresholds and provide sustained autonomous observations within a reef zone that can be coupled to modeled oceanic fields
   - This will enable NOAA to evaluate if the seasonal changes they observe offshore are directly reflected in the carbonate chemistry of the near-reef environment or if they are decoupled as result of the metabolic control imparted by the reef itself and/or mineral buffering
   - Partners include NOAA's Coral Reef Conservation Program, NOAA AOML, RSMAS, and the University of Puerto Rico
   - La Parguera, Puerto Rico, is the pilot site for a 5-year project (FY08 -12) where a MAPCO2 system (which monitors atmospheric and surface water pCO_2) is being deployed
   - Together with regular geochemical sampling and hydrodynamic modeling, the project team hopes to demonstrate an effective monitoring approach to provide sustained long-term observations that is suitable for deployment in remote areas

14) Develop educational and informational materials to communicate the implications of ocean acidification for reef ecosystems and dependent communities emphasizing response actions.

A centerpiece of this Declaration is to develop materials and outreach activities that communicate the societal implications of ocean acidification. These materials should have an educational role, i.e., delivering content when appropriate, and highlight the intrinsic value of coral reefs as a natural treasure, whose vivid colors and thriving diversity have captivated people for decades and provided key goods and services for millennia. Informational and educational materials will need to be targeted at selected audiences (e.g., general public, tour operators, fishers, politicians, school children), emphasize the implications and impacts of ocean acidification, and include the need for changes in conservation management policies and approaches as well as behavior on and near coral reefs.

The materials generated will need to be in three categories.

- *Informal public education*: Materials and displays that provide an overview of the science behind ocean acidification and raise appreciation of it as a creeping environmental problem, may be used at aquaria, in film and video, and in signage at important natural sites. Opportunities to work with specialists in informal public education in the USA include, for example, the American Museum of Natural History and the Monterey Bay Aquarium as both institutions are already developing displays on the impacts of ocean acidification.
- *Web presence and material*: ocean acidification web materials should be developed and shared among the many websites that include key information on coral reefs or ocean acidification, including, among others:
  NOAA Coral Reef Watch (http://coralreefwatch.noaa.gov/)

the Great Barrier Reef Marine Park Authority's Climate Change site (http://www.gbrmpa.gov.au/corp_site/key_issues/climate_change)
The Nature Conservancy's Reef Resilience site (http://www.reefresilience.org/home.html)
Coral Reef Alliance (http://www.coral.org/)
EPOCA (http://epoca-project.eu/)
The Ocean Acidification Network (http://www.ocean-acidification.net/)
The materials should include entry-level "surfable" content and submissions from the scientific community. There should also be an emphasis on developing useful sources for the media and educators.

- *Development of K-12 curriculum units via partnerships with teachers:* Managers and scientists should seek ways to form partnerships with K-12 educators to develop curriculum units that meet the science criteria for various age groups and regions. These units and materials could be shared and distributed via the web.

15) Integrate the threat of ocean acidification into existing and new climate change programs and assessments.

The relatively recent awareness of the importance of ocean acidification means that many climate change programs and assessments do not explicitly include this issue. Monitoring programs should be reviewed to identify opportunities for filling knowledge gaps about ocean acidification for coral reefs. Funds should be allocated or sought so that monitoring programs can be expanded to provide critical information relating to ocean acidification, as well as increasing sea temperatures and sea level. Regional and international assessments (e.g., sectoral vulnerability assessments; IPCC Assessment Reports) should also be reviewed to ensure they adequately capture current knowledge about ocean acidification, highlight potential responses, and define critical knowledge gaps. Research programs should also be reviewed to ensure that the immediate and long-term information needs relating to ocean acidification are appropriately prioritized and funded.

Major opportunities exist to apply ocean acidification adaptation actions over vast geographic scales through programs that either directly implement coral reef conservation or provide critical technical and financial support to them. Examples of such opportunities include:

- Programs financed by multinational organizations such as the World Bank and the Global Environment Facility, bilateral development support agencies, private foundations, and international non-governmental organizations – all of these organizations have the capability to provide funds and/or science and technical advice to help integrate climate change responses into coral reef conservation programs
- Regional programs that commit to shared priorities and strategies such as the Micronesia Challenge, the Caribbean Challenge, the Coral Triangle Initiative, the Global Island Partnership, and CORDIO, all of which offer the opportunity to integrate climate change responses into their collaborative programs over vast geographic areas

- National programs such as those implemented by the Great Barrier Reef Marine Park Authority, the NOAA Coral Reef Conservation Program, and many others with a smaller geographic focus that collectively cover all the major reef areas of the world

APPENDIX C

Background text on the impacts of ocean acidification on coral reef ecosystems

Carbon dioxide is one of the most important gases in the atmosphere affecting the radiative heat balance of the earth. For the 650,000 years prior to the industrial revolution, atmospheric CO_2 concentrations remained between 200 to 280 parts per million (ppm). As a result of the industrial and agricultural activities of humans, current atmospheric CO_2 concentrations are around 385 ppm, increasing at about 0.5% per year. The atmospheric concentration of carbon dioxide is now higher than experienced on Earth for at least the last half million years, and is expected to continue to rise, leading to significant temperature increases by the end of this century. The global oceans are the largest natural reservoir for this excess carbon dioxide, absorbing approximately one-third of the carbon dioxide added to the atmosphere by human activities each year (Sabine et al. 2004). It is now well established that there is a strong possibility that the partial pressure of CO_2 in the ocean surface will double over its pre-industrial value by the middle of this century, with accompanying surface ocean acidity (pH) and carbonate ion (CO_3^{-2}) decreases that exceed those experienced during the transition from glacial to interglacial periods. The process of absorption of anthropogenic CO_2 by the oceans has benefited humankind by significantly reducing the greenhouse gas levels in the atmosphere and thus reducing the global warming impact on the planet. However, the uptake of carbon dioxide by the ocean is starting to take its toll on the chemistry of the seawater. The pH of the ocean surface waters has decreased by about 0.1 units from an average of about 8.16 to 8.05 since the beginning of the industrial revolution due to uptake of CO_2 (Feely et al. 2004). A doubling of the concentration of atmospheric carbon dioxide is predicted to correspond with an average sea surface pH drop to about 7.91, and a tripling of atmospheric carbon dioxide, which could happen by 2100, with a pH of 7.76 (Orr et al. 2005). Moreover the rapid rate of change is unprecedented, constituting an abrupt change in the marine environment.

Ocean acidification likely will impact the ability of marine calcifiers, including corals, foraminifera, coccolithophorids, and molluscs, to make shells and skeletons from calcium carbonate. This will occur principally because of a reduction in the availability of the chemical constituents needed for calcified shells and plates. Both laboratory and field studies have provided evidence for deterioration of many species of marine organisms that produce calcium carbonate shells due to increasing carbon dioxide levels in seawater and the resulting decline in pH (Kleypas et al. 2006). For example, increasing seawater acidification has been shown in controlled studies to significantly reduce the ability of reef-building corals to produce their skeletons, affecting growth of individual corals and making the reef more vulnerable to erosion (Langdon and Atkinson 2005; Yates and Halley 2006). Some estimates indicate that at atmospheric CO_2 levels close to 2-3 times the pre-industrial levels coral reefs may erode faster than they can be rebuilt potentially making them less resilient to other environmental stresses (e.g., disease, bleaching, storms). Laboratory results indicate that coral reefs cannot adapt to this changing seawater chemistry (Langdon 2002). This could compromise the long-term viability of these ecosystems, perhaps impacting the thousands of species that depend on the reef habitat.

The impact of ocean acidification on fisheries and coral reef ecosystems could reverberate through the U.S. and global economy. The U.S. is the fifth largest seafood consumer in the world with total consumer spending for fish and shellfish around $60B per year (NOAA 2008). Coastal and marine commercial fishing generates upwards of $30B per year and employs nearly 77,000 people (NOAA Fisheries Office of Science and Technology). Healthy coral reefs are the foundation of many of these viable fisheries, as well as the source of jobs and businesses related to tourism and recreation. Approximately half of all federally managed fisheries depend on coral reefs and related habitats for a portion of their life cycles. The National Marine Fisheries Service estimates the value of coral reefs to U.S. fisheries is over $100 billion. Local economies also receive billions of dollars from reef tourism. In Florida, for example, coral reefs attract more than $1.6 billion in tourism annually (Bryant et al. 1998). Worldwide, coral reefs sustain a local tourism economy that makes up 10 percent of all jobs (NOAA Coral Reef Conservation Program). Plus, coral reefs provide vital protection to coastal areas that are vulnerable to storm surges and tsunamis. Much remains unknown with regards to the future impacts of ocean acidification. The overarching need is to provide society advanced warning of the consequences of ocean acidification, sufficient to develop adaptive strategies. Accurate forecast models are required to understand the full breadth of the impacts on both marine ecosystems and the societies dependent on them.

Research should look carefully at the calcification response of organisms from extreme or unusual environments that are subject to elevated CO_2 and low saturation state. Such organisms may possess unusual adaptations that allow them to survive under conditions that are stressful to calcifiers that are not used to low saturation conditions. Resource managers should be encouraged to protect reef ecosystems in areas that may benefit from seawater buffering due to carbonate sediment dissolution. Also resource managers should be encouraged to reduce other anthropogenic impacts on reefs (e.g., nutrients, contaminants, terrestrial run-off, over fishing, etc.) in order to reduce pressure from multiple stressors and give reefs the “best shot” at coping with elevated CO_2 levels. Some studies suggest that it may be possible to subject corals to episodic increases in nutrients or bicarbonate in order to reduce the sensitivity of corals to increased levels of CO_2 (Langdon and Atkinson 2005; Rau and Caldeira 1999; Caldeira and Rau 2000; Caldeira et al. 2005). However, more research on these approaches is needed. Of course, the best strategy would be to slow down or stop the increase in the rate of CO_2 emissions into the atmosphere. This could provide an opportunity for the marine calcifiers to adapt to changes in atmospheric CO_2 on timescales they are able to respond to. However, it is still unclear whether or not corals and other marine calcifiers are able to adapt to changing atmospheric CO_2 concentrations on timescales of importance to humankind (i.e., a few decades to hundreds of years). More research is required before these assessments can be made with any certainty.

APPENDIX D

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