Ocean Acidification—Management

The increasing carbon dioxide (CO_2) concentration in the Earth's atmosphere is absorbed by the oceans and leads to changes in ocean carbon chemistry. This process of ocean acidification results in a range of biological and socioeconomic impacts. Accelerating acidification under current rates of CO_2 emissions is expected to compromise the function of global marine ecosystems during this century. Management actions are urgently needed to help counteract these impacts.

The concentration of carbon dioxide (CO_2) in the Earth's atmosphere has increased dramatically since the Industrial Revolution (from around 280 parts per million [ppm] in preindustrial times to 392 ppm in 2011), primarily due to human activities such as the burning of fossil fuels and land-use activities (IPCC 2007). This buildup of CO_2 is recognized as one of the primary causes of global climate change. Over the last few decades, only half of the CO_2 released by human activities has remained in the atmosphere; 25 percent has been absorbed into the oceans (Sabine et al. 2004). This absorptive capacity of the oceans has helped to buffer the impacts of global warming associated with increased atmospheric CO_2 emissions, but it has come at a cost in the form of ocean acidification.

When atmospheric CO_2 dissolves into seawater, carbonic acid is formed, and hydrogen ions are released. As a result, the pH of the ocean surface waters decreases, making it more acidic. On the 14-point pH scale, lower numbers (0–6.9) designate acidic water, while higher numbers (7.1–14) designate basic water; a pH of 7.0 is neutral. Oceans are naturally slightly basic (on average, pH > 8.1), and acidification via CO_2 uptake is expected to drive pH as low as 7.6 by the end of this century. This pH change will affect the ocean carbon chemistry system, and the biological and ecological processes that depend on it in numerous ways.

When hydrogen ions are released in seawater, they combine with carbonate ions (forming bicarbonate), thereby lowering the carbonate ion concentration. Carbonate ions are the building blocks (calcifiers) for the shells and skeletons of many marine organisms, such as corals, crustaceans (e.g., lobsters and crabs), and mollusks (e.g., clams and oysters). Lowering the pH thus reduces the saturation state of calcium carbonate, which makes it harder for organisms to form the calcium carbonate needed for their shells. Calcification, or the process of "shell building," depends on the availability (saturation) of carbonate ions in seawater. The calcification rates of marine calcifiers are generally sensitive to a decline in carbonate ion concentration. More specifically, changes in the carbonate ion concentration in the oceans can affect the saturation state—and hence biological availability—of several forms of calcium carbonate that these species depend on for shell building, including calcite, aragonite, or high-magnesian calcite (Feely, Doney, and Cooley 2009).

Currently, calcifying marine organisms in most areas of the ocean surface can build skeletons and shells because the water is saturated with calcium carbonate (Pelejero, Calvo, and Hoegh-Guldberg 2010). The pH of the ocean surface waters has already decreased, however, by about 0.1 units since the beginning of the Industrial Revolution (Feely et al. 2004), reducing the saturation of aragonite or calcite that these organisms need. Because the pH scale is logarithmic, a 1-unit decrease in pH is equivalent to a tenfold increase in acidity. Ocean pH is projected to drop an additional 0.4 pH units by 2100 under a high CO_2 emission scenario (IPCC 2007), with carbonate saturation levels potentially falling below those required to sustain coral reef accretion (Royal Society 2005; Hoegh-Guldberg et al. 2007; Silverman et al. 2009). Such changes in the carbon chemistry of the open ocean probably have not occurred for more than 20 million years (Feely et al. 2004).

Changes in ocean acidity vary globally. High-latitude surface waters (waters near and right below the North and South Poles) have a naturally low concentration of carbonate ions because atmospheric CO_2 is more soluble in colder seas. As a result, these waters experience a higher degree of ocean acidification than warmer ocean waters and are therefore likely to become undersaturated with respect to aragonite before tropical and subtropical waters (Feely et al. 2004). Models suggest that oceanic waters will be undersaturated with respect to aragonite by 2020 in the Arctic Ocean and by 2050 in the Southern Ocean surrounding Antarctica (Orr et al. 2005; Steinacher et al. 2009).

Tropical coral reefs are also vulnerable to ocean acidification. Some globally important coral reef regions, such as the Great Barrier Reef, the Coral Sea, and the Caribbean Sea, are projected to attain dangerously low states of aragonite saturation more rapidly than other regions such as the Central Pacific Ocean (Hoegh-Guldberg et al. 2007). Despite global ocean acidification patterns, a number of local-scale ecological processes affect the rate and geographic scale of ocean acidification. Large variations in pH and aragonite saturation states have been documented on some coral reefs. On Heron Island Reef in the Great Barrier Reef, Australia, for example, variations in pH and aragonite saturation state over the course of one day were greater than the predicted changes that ocean acidification will cause for the oceans globally by the middle of the century (Anthony et al. 2008; 2011). These results suggest that although general patterns in aragonite saturation are evident for open oceans, they will vary significantly both spatially and temporally as a result of reef-scale processes.

Climate change and ocean acidification challenge marine conservation managers and research scientists because they force them to try to manage global threats at local scales. Unlike other global stressors, such as increasing sea surface temperature that leads to bleaching (visible whitening) and widespread mortality of coral reefs, ocean acidification is largely an invisible, insidious environmental problem. Because of the relatively recent awareness of the threat of ocean acidification, little guidance for managing its impacts exists. Further, the majority of research is focused on addressing the responses of marine organisms to changes in ocean chemistry or on projecting global-scale changes in ocean chemistry; little emphasis has been placed on developing management or policy recommendations to address these impacts (but see Mcleod et al. 2008).

Impacts of Ocean Acidification

A number of groundbreaking studies conducted in the late 1990s predicted that coral reefs would show dramatic responses to changes in ocean chemistry during the twenty-first century (Gattuso et al. 1998; Kleypas et al. 1999; Marubini and Atkinson 1999). Since then, the effects of ocean acidification on marine organisms and ecosystems have become increasingly evident through experimental and observational research. Ocean acidification has demonstrable impacts on a number of biological and ecological processes in many marine groups—including phytoplankton, corals, other invertebrates, and fishes—around the globe (Kroeker et al. 2010). Most studies have focused on impacts of ocean acidification on calcification (shell building) and dissolution (shell dissolving or disruptions in formation), but impacts on other processes such as early life-history stages are reported with increasing frequency (Dupont and Thorndyke 2009; Albright and Langdon 2011). For example, ocean acidification can lead to excessive CO_2 levels in the blood (CO_2 toxicity) of fish and cephalopods and significantly reduced growth and fecundity in some invertebrates (Orr et al. 2005). For species with long generation times, slower growth and lower fecundity can lead to population declines. Recent works indicate that ocean acidification may lead to sensory and neurological dysfunction in marine fish larvae—that is, they can't "smell" the reef and thus fail to distinguish predators from parents (Munday et al. 2010).

Importantly, ocean acidification doesn't affect all marine organisms equally. Some hard corals have linear responses while others show accelerating responses to reductions in carbonate ion concentration (Reynaud et al. 2003; Jury, Whitehead and Szmant 2009; Rodolfo-Metalpa et al. 2010). While accelerating responses may result in a catastrophic tipping point for some species, it is not yet possible to define such critical points for individual species or broader ecosystem changes. The ability to define tipping points is limited because most studies on ocean acidification impacts are based on experimental work over short time scales and for a single species. Little is known about how populations and ecosystems will respond to ocean acidification, the combined effects from other stressors (e.g., pollution, overfishing, increasing ocean temperatures), and the ability of organisms to adapt. The variety of responses of marine organisms is partially the result of the wide variety of processes that ocean acidification affects, such as dissolution and calcification rates, growth rates, development, and survival (Kroeker et al. 2010). This variation in responses makes predicting the impacts of ocean acidification on species and marine ecosystems complex. Despite these complexities, however, recent studies indicate that, overall, ocean acidification will harm calcifying marine organisms (Hendriks, Duarte, and Alvarez 2010; Kroeker et al. 2010).

Whereas recent studies have explored the biological impacts of ocean acidification on marine organisms, less emphasis has been placed on assessing the socioeconomic impacts. Because ocean acidification affects marine organisms' abilities to form shells, it may decrease the abundance of commercially important shellfish species such as clams, oysters, and sea urchins, affecting the human communities that depend upon these resources for food and/or livelihoods (Cooley, Kite-Powel, and Doney 2009). Ocean acidification may thus affect human communities through a loss of goods and services provided by ecosystems such as coral reefs—for example, tourism revenues, fisheries, coastal protection, and cultural values. Such goods and services are valued in billions of dollars (Burke et al. 2011). The Great Barrier Reef, for example, contributes more than $5 billion annually to the Australian economy (Access Economics 2005).

Additional research is needed to assess the deeper socioeconomic impacts of ocean acidification in countries whose communities directly depend upon natural marine resources for survival (Cooley and Doney 2009). Such research could provide motivations for action that extend beyond ocean acidification and climate change, because economic analyses and models of ocean acidification's impacts on fisheries and tourism are necessary to understand the true comprehensive costs of action or inaction to reduce global CO_2 emissions (Fulton et al. 2011).

Potential Management Options

The most critical action needed to address ocean acidification is to stabilize atmospheric CO_2 concentrations. Reviews suggest that policies that allow the global average atmospheric concentration of CO_2, currently approaching 393 ppm to reach or surpass 500 ppm of CO_2 are likely to be extremely risky for corals reefs (e.g., Hoegh-Guldberg et al. 2007). Thus, ocean acidification provides another impetus for comprehensive and effective global policies to address CO_2 emissions.

Unfortunately, reducing global emissions is beyond the scope of marine conservation managers. A more immediate need is to identify and implement local actions that support marine ecosystem (e.g., coral reef) health in the face of global threats such as ocean acidification. A study by the National Research Council (2010, 85), *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean*, reviewed the current state of the knowledge of ocean acidification and stated that "there is not yet enough information on the biological, ecological, or socioeconomic effects of ocean acidification to adequately guide management efforts." This conclusion is based on the fact that most research has focused on the impacts of ocean acidification on few species over short time scales. As a result, there are major research gaps regarding ocean acidification's larger importance, including how ocean acidification will affect many ecologically or economically important species and communities, how it will affect a variety of physiological and biogeochemical processes, and what the potential will be for organisms to adapt to projected changes in ocean chemistry (Boyd et al. 2008).

The science needed to address these gaps will probably take decades to fully develop. Waiting to take management action until the science is complete, however, may put critical marine ecosystems at risk. Local actions can and should be taken now to protect marine ecosystems. Such actions include reducing the other stressors that affect most marine ecosystems, such as declining water quality, coastal pollution, and overfishing of important species and functional groups, such as herbivores (Hughes et al. 2003). Reducing land-based sources of pollution, such as nutrient runoff from agriculture and sediment runoff from coastal development, is particularly important for managing the impacts of ocean acidification, because nutrients like phosphorus and nitrogen and land-based carbon inputs can lower pH and aragonite saturation states in coastal and oceanic waters (Andersson, Mackenzie, and Lerman 2006). To achieve these goals, marine management efforts must be integrated with land-use and coastal-zone planning and practices to help reduce pollutant inputs. More generally, the reduction of stressors on marine ecosystems supports ecosystem health and will better allow marine organisms to channel resources to growth, calcification, and reproduction rather than to repairing damage and recovering from disease (Mcleod et al. 2008).

Current ocean acidification research is exploring differences in the sensitivity of marine species and habitats to changes in ocean chemistry. If scientists can identify species or habitats that are less vulnerable to the impacts of ocean acidification, these could become priorities for inclusion in marine protected areas (MPAs). Less vulnerable areas may include coral reefs in carbonate rich areas, such as places where there are raised reefs and limestone islands, extensive reef flats, patch reef/coral head complexes, and carbonate sediment deposits. Other candidate areas for increased protection through MPAs may be high-diversity reef complexes that are well flushed by oceanic water, because these influxes of fresh oceanic water bring higher total alkalinity and saturation states that support reef and shell building. Well-flushed areas may be more vulnerable in the future, however, if ocean acidification causes significant decreases in the pH of oceanic waters. Therefore, a strategy of spreading the risk by selecting examples of coral reef areas in a variety of ocean chemistry and oceanographic regimes is a useful MPA design approach. By protecting multiple examples of such reef areas, MPA managers are helping to ensure that these ecosystems are more likely to survive climate and other human threats.

Coral reefs located in areas with high variability in seawater temperature are thought to be less vulnerable to thermal stress and associated bleaching and mortality caused by increases in sea surface temperature (McClanahan et al. 2007). If reefs in areas with high natural variability in ocean chemistry are also less vulnerable to ocean acidification, then managers could prioritize reefs in these areas for inclusion in MPAs. In the absence of such information, MPA managers may choose to locate MPAs in a range of ocean chemistry regimes (including areas with high and low variability). Additionally, selecting reefs in a variety of pH and aragonite saturation regimes increases the chances that managers will identify and protect corals that are acclimated to a variety of pH conditions and spreads the risk of any coral species' survival being compromised by ocean acidification.

Actions that address threats such as increasing sea level, increasing sea surface temperature, and ocean acidification must be incorporated into MPA management plans to reduce the impacts of increasing atmospheric concentrations of CO_2 on marine species and ecosystems. It is also important to develop and test the efficacy of innovative interventions that reduce the effects of ocean acidification on high-priority areas and species. Such interventions include CO_2 capture and storage strategies. The geographic scale, time frame, and economic and environmental costs and benefits of these interventions must be explored further before they can be implemented.

Research Needs and Next Steps

A number of priority research needs should be addressed to support the management of ocean acidification. While models can project changes in ocean chemistry at global and regional scales, these models do not take coastal processes into account. Coastal areas already experience extreme variability in water chemistry because of natural and human inputs, such as acidic discharge of river water (Salisbury et al. 2008), atmospheric deposition of nitrogen and sulfur (Doney et al. 2007), and eutrophication resulting from land-use changes and agriculture, a process where a body of water (in this case the ocean) receives excess nutrients that stimulate algal growth (Borges and Gypens 2010). The processes that affect coastal carbonate chemistry are complex and not well resolved, and improved understanding is needed to manage the responses of marine organisms, ecosystems, and industries in coastal areas (National Research Council 2010).

The mitigation of local causes of ocean acidification using existing environmental laws has been proposed recently (Kelly et al. 2011). Local and state governments have the authority and capacity to address many stressors that can exacerbate ocean acidification conditions in coastal waters. For example, enforcement of the US Clean Water Act can help ensure that precipitation runoff and associated pollutants, which can increase acidification, are limited. Controlling coastal erosion can help reduce nutrient and sediment loading of water; such coastal inputs also may be enriched with fertilizers that can increase acidification, providing another reason for reducing them. Changes in land-use patterns, such as changes in deforestation practices, can reduce direct and indirect CO_2 emissions, runoff, and other threats. Enforcing federal emission limits for pollutants such as nitrogen oxide and sulfur oxide (e.g., from coal-fired power plants) can help reduce ocean acidification impacts in coastal waters (Kelly et al. 2011). Despite the clear benefits of minimizing additional stressors on coastal ecosystems through enforcement of existing environmental laws, such actions are inadequate to reverse the impacts of ocean acidification at a global scale.

To help conservation managers identify and protect marine species and communities that are most likely to survive changes in ocean chemistry, additional research is needed to investigate the response of organisms, populations, and communities to ocean acidification. Further, research exploring the capacity of marine organisms to acclimatize or adapt to changes in ocean chemistry will be important in understanding their susceptibility to future changes. The ability to identify species that are less vulnerable to changes in ocean chemistry is also useful to support aquaculture programs, because such species may be used for selective breeding. Field studies that document changes in ecosystem structure and function over natural pH gradients are also useful for highlighting thresholds that trigger widespread ecological and biological changes. The ability to identify indicators of regime shifts (e.g., from coral to algal dominance) helps marine managers take actions to avoid such shifts or cope with them (Anthony et al. 2011).

No impact occurs in isolation, so studies need to address the interactive effects of multiple stressors. Marine ecosystems currently must deal with changes in ocean pH in addition to increasing sea surface temperatures, changes in sea level, and other human impacts such as pollution, coastal development, and overfishing. It may be challenging for researchers to attribute ecosystem changes to a specific stressor given the suite of challenges facing marine ecosystems. Managers, however, need the ability to understand how species, communities, and ecosystems respond to ocean acidification in concert with additional stressors in order to predict changes and develop appropriate management responses.

Decision makers need socioeconomic research on the impacts of ocean acidification, the projected timing of impacts, and ways to increase adaptability and resilience of socioeconomic systems. To prioritize research and mitigation and adaptation activities, assessments of the cost of ocean acidification on marine ecosystems and resources are essential. More broadly, the public needs educational and informational materials that communicate the implications of ocean acidification on marine ecosystems and dependent communities, and that emphasize actions that can be taken to reduce these impacts.

The ecological, biological, and socioeconomic impacts of ocean acidification pose significant challenges to marine species and the human communities who depend upon them for food and livelihoods. Anthropogenic CO_2 emissions must be dramatically reduced to mitigate these impacts. Our best hope for tackling the challenge of ocean acidification is the implementation of a suite of four key management actions: (1) curb and stabilize atmospheric CO_2 concentrations; (2) protect marine species and areas likely to be less vulnerable to ocean acidification; (3) explore and apply CO_2 capture and storage methods where feasible; and (4) use existing environmental laws to control stressors that exacerbate ocean acidification conditions in coastal waters.

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See also Catchment Management; Coastal Management; Ecological Restoration; Eutrophication; Fisheries Management; Food Webs; Global Climate Change; Indicator Species; Large Marine Ecosystem (LME) Management and Assessment; Marine Protected Areas (MPAs); Pollution, Nonpoint Source; Pollution, Point Source; Regime Shifts; Resilience

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