Anticipating Ocean Acidification's Economic Consequences on Commercial Fisheries

By Sarah R. Cooley and Scott C. Doney

MANY VALUABLE COMMERCIAL FISHERIES AND AQUACULTURE FACILITIES *harvest ocean shellfish (e.g., clams, scallops) and crustaceans (e.g., lobsters, crabs) that form calcium carbonate shells. These animals, along with corals, may be particularly sensitive to changes in seawater chemistry driven by human fossil fuel use. Finfish may also be affected indirectly owing to loss of prey and habitat. Ocean acidification impacts could decrease future fishing revenues and harm communities that depend economically and culturally on marine resources.*

In many parts of the United States, the word "seafood" is nearly synonymous with carbonate shell-forming marine species—shellfish like oysters, clams and scallops, and crustaceans like lobster, crabs, and shrimp. Adults and juveniles of these very economically valuable animals, along with less familiar shelled creatures like sea urchins, planktonic snails called pteropods, and some types of phytoplankton, are food for a variety of predators and fuel food webs. Commercial harvests of shellfish, crustaceans, and finfish sustain seafood industries that support many coastal economies. If ocean acidification slows the growth of marine organisms' carbonate shells and skeletons, it will endanger many individual plants and animals, whose declines will in turn harm entire marine food webs, aquatic environments, and economies (Doney et al. 2009).

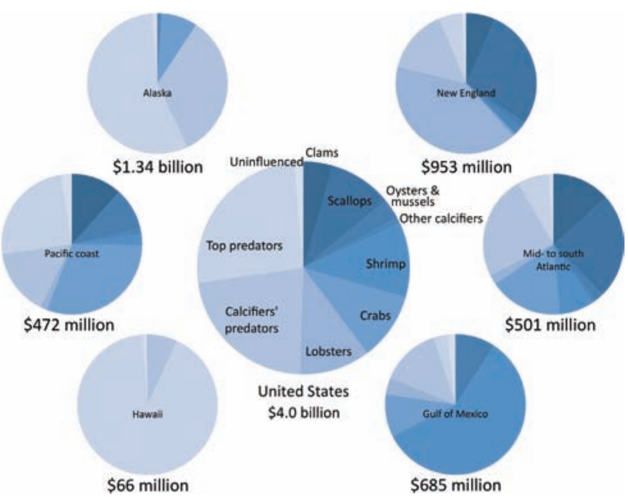

Figure 1. Primary revenue from U.S. commercial fishing (the amount paid to fisherman for the catch, sometimes called ex-vessel revenue) for the U.S. as a whole and broken up by region. Data are for 2006 from National Marine Fisheries Service statistics. The pie charts are divided into groups of species and the darker colors indicate those groups that are directly sensitive to ocean acidification, such as shellfish and crustaceans.

Recreational	Total economic impact (sales, income, jobs)	$82 billion
	Jobs supported	~530,000
Commercial	Primary sales (the amount paid to fishermen for catch)	$4 billion
	Retail seafood sales	$70 billion
	Net contribution to GNP	$35 billion

Table 1. Revenues from U.S. recreational (Gentner and Steinback 2008) and commercial (NMFS statistics) fishing (US dollars).

AN ECONOMIC ASSESSMENT OF U.S. COMMERCIAL FISHING AND AQUACULTURE

Commercial fishing is a big business today in the United States, and carbonate shell-forming species provide a large portion of its revenues. In 2006, the total value of commercial sales from fishermen to middlemen was $4.0 billion; shellfish and crustaceans provided 50% of that amount (Figure 1; Andrews et al. 2007). The contribution varies by region around the country (Figure 1); shellfish are more important in the New England and mid- to south Atlantic, crustaceans contribute greatly to New England and Gulf of Mexico fisheries, and predatory finfish (e.g. pollock, salmon, and tuna) dominate the Alaskan, Hawaiian, and Pacific-territory fisheries. Subsequent processing, wholesale, and distribution of all harvests generated retail sales of $70 billion in 2006, leading to $35 billion added to the U.S. gross national product that year (Table 1; Cooley and Doney, submitted).

Across the country, the number of jobs generated by U.S. commercial fisheries also grows markedly from catch to retail sale. The total number of jobs in the United States supported by commercial fishing is difficult to constrain, because industry surveys do not count self-employed fishermen and may not count all middlemen. However, the efforts of a few fishermen support many jobs in seafood processing, transportation, preparation, and sales. Commercial fish processing and wholesaling nationwide supported about 70,000 jobs in 2006.

Recreational fishing also adds economic benefits because recreational fishermen travel, purchase permits and equipment, and patronize supporting industries (Figure 2). This results in the generation of jobs, profits, tax revenues, and business-to-business revenue. In 2006 (the latest date for which data is available), $24 billion of income, a total impact of $82 billion from sales and services, and almost 530,000 jobs (Table 1) were created in the United States by recreational saltwater fishing for a total economic impact of $82 billion that year (Gentner and Steinback 2008).

Figure 2. Saltwater recreational fishing is critical to local and regional economies throughout the United States (SE Alaskan waters pictured). The National Marine Fisheries Service estimates that 25 million saltwater anglers fished 127 million days in the coastal states of the U.S. in 2006.

Figure 3. The American lobster (*Homarus americanus*). Found along the Atlantic coast of North America, American lobsters live a solitary and largely nocturnal existence, feeding on crabs, mollusks, sea urchins, fish, and even macroalgae. Changes associated with ocean acidification may impact lobsters both directly since they use calcium carbonate to form their shells and indirectly through impacts to their food sources.

Growing aquaculture industries worldwide also depend heavily on carbonate-forming organisms like shellfish and crustaceans. In total, 20-25% of the global per capita human consumption of animal protein comes from marine harvests, but patterns of consumption vary widely, and developing and coastal nations often consume high per capita quantities of aquaculture products. In the United States, aquaculture generated $1 billion of primary sales in 2005 (Andrews et al. 2007), approximately 25% of the value of commercial wild fish harvests. Most aquaculture facilities are located in coastal areas, which will also experience ocean acidification.

	Species	pH	Shell dissolution	Increased mortality	Other
Mussel	*M. edulis*	7.1	yes	yes	25% decrease in calcification
Oyster	*C. gigas*	7.1	n/a	n/a	10% decrease in calcification
Giant scallop	*P. magellanicus*	< 8.0	n/a	n/a	Decrease in fertilization, development
Clam	*M. mercenaria*	7.0-7.2	yes	yes	
Crab	*N. puber*	6.0-8.0	yes	n/a	Lack of pH regulation
Sea urchin	*S. purpuratus*	6.2-7.3	yes	n/a	Lack of pH regulation
Dogfish	*S. canicula*	7.7	n/a	yes	
Sea bass	*D. labrax*	7.25	n/a	n/a	Reduced feeding

Table 2. Responses of commercially harvested species to laboratory ocean acidification experiments "n/a"—not available, response is unknown.

DIRECT CONSEQUENCES FOR SHELLFISH AND CRUSTACEANS

Although the full consequences of ocean acidification are not yet known for most commercially valuable species, trends for a few species (determined from laboratory studies) are alarming, indicating that the number and quality of many carbonate shell-forming species may decrease (Table 2; Doney et al. 2009). Because ocean acidification decreases seawater pH and carbonate saturation state, the carbonate shells of many marine plants and animals grow more slowly, or even shrink below certain pH and saturation state thresholds (Figure 3; see Guinotte and Fabry, this issue). The effects of acidification on juvenile marine organisms, however, are largely unknown; if acidification damages juveniles at a key developmental stage, entire populations could be threatened. One cause for concern is that many shellfish grow their juvenile shells from a more soluble form of carbonate and thus may be more susceptible to changes in chemistry. In the worst-case scenario, multiple recruitment failures could cause a population to collapse even if ocean chemistry remains in a range acceptable for adults. In other cases, carbonate-forming organisms that are able to maintain their shells and skeletons in acidified conditions may expend so much energy doing so that their reserves for survival and reproduction may become limited.

Protecting vulnerable marine organisms grown in aquaculture facilities from the effects of ocean acidification may be possible in theory, but it presents practical challenges. Aquaculture is often conducted in tanks or ponds on land that are filled with coastal seawater or within coastal ocean pens. Adjusting seawater chemistry before supplying culture tanks on land would require a great deal of equipment and monitoring that would dramatically increase the overhead of aquaculture operations. Aquacultured animals in nearshore pens cannot be shielded from ocean acidification.

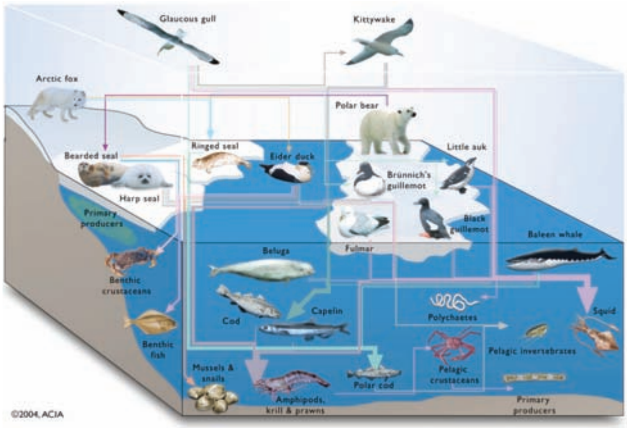

Figure 4. Trophic linkages in the Beaufort Sea. The food web of polar areas such as the Beaufort Sea demonstrates the complex interconnections that are at risk from ocean acidification. Because many Arctic animals depend either directly or indirectly on shellfish for food, reductions in the productivity of these waters due to ocean acidification and changing climatic conditions threaten the base of this and other marine ecosystems.

Laboratory experiments show that oysters and mussels' growth rates decrease and their calcification rates decline by 10% and 25%, respectively, in simulated future ocean conditions when atmospheric pCO_2 reaches 740 ppm, a level that would occur by about 2060 in seawater unless CO_2 emissions are controlled. If decreasing calcification rates observed in the laboratory cause comparable population losses in nature, a 10-25% decrease in all shellfish and crustacean harvests in 2006 would have decreased primary sales from U.S. commercial fisheries by $200-500 million (Cooley and Doney, submitted). In the future, economic losses will likely vary as marine ecosystems respond and adapt differently to acidification and as economic conditions change. Refining economic loss estimates requires knowing the responses of organisms to ocean acidification, the effects of adaptation or conservation measures enacted in the next 50 years, and the total economic consequences of fishing losses.

INDIRECT CONSEQUENCES FOR FISHERIES AND SOCIETIES

Beyond their direct commercial value, many calcifying species are located at the bottom or middle of the marine food web; therefore, the effects of ocean acidification will likely be transmitted throughout ecosystems by predator-prey relationships (Figure 4; Doney et al. 2009). Nearly all commercially harvested

ECONOMIC IMPACTS OF OCEAN ACIDIFICATION ON LOCAL ECONOMIES

Complicating the estimation of ocean acidification's broader economic effects is the difficulty in quantifying indirect links among marine ecosystems and regional economies. New Bedford, Massachusetts, is an example of a city that could be disproportionately affected by economic losses brought on by ocean acidification (Cooley and Doney, submitted). New Bedford has historically relied on fishing income and currently hosts a large scallop fleet. In 2006, New Bedford had the largest commercial fishing revenues of any single city, about $280 million in primary sales, almost all from shellfish. This region already has little economic resilience; 20% of its population fell below the poverty line in 1999, approximately twice the statewide (9%) and nationwide (11%) rates that year. In addition, the income gap separating the highest- and lowest-income families is growing at the sixth fastest rate nationwide. Fishery losses in a city like New Bedford could continue to alter its economy and demographics and further accelerate the income gap's development.

wild finfish species prey to some extent on shellfish and crustaceans or their predators. Depletion of calcifying prey would alter or remove traditional food sources and intensify competition among predators for remaining prey species. This indirect pressure would likely reduce harvests of commercially important predators at the same time ocean acidification would directly pressure populations via metabolic or reproductive stress. The overall impact of losing calcifiers on predator numbers is not well known, but the total ecosystem impact of ocean acidification will certainly depend on whether alternative prey species are available and whether predators can switch to prey species that are not affected by acidification.

Coral reef damage associated with ocean acidification will also indirectly pressure marine ecosystems by disrupting the feeding and reproduction of numerous reef-dependent species. Declines in commercially and/or ecologically important species could follow as a result of decreased recruitment or increased success of competitors. In addition to creating unique ecosystems, reefs generate income and economic development from fishing and recreational diving.

If losses of plankton and juvenile shellfish alter marine food webs and losses of coral reefs eliminate habitat, entire ecosystems can shift into entirely new configurations after a sudden disturbance pushes these stressed communities past an ecological "tipping point." This progression is well understood in coral reef ecosystems that have been chronically damaged by temperature or pathogens; ocean acidification is expected to cause similar harm. Continuously stressed reefs become less ecologically resilient, meaning that they are less able to return to a stable, diverse coral community after a disturbance like a storm. Reefs damaged by such short-term events often then become dominated by macroalgae, and species diversity decreases (Hoegh-Guldberg et al. 2007). Herbivores, which tend to be less commercially desirable than predatory reef species, populate the reef. Perturbed ecosystems like these damaged reefs have lower biodiversity, are more susceptible to further injury, and provide fewer ecological services for humans. The mechanisms and outcomes of ecosystem shifts in non-coral reef communities (e.g., estuaries or coastal habitats populated by carbonate-forming organisms) are not as well understood, but non-coral communities may also undergo similar major shifts if plankton and juvenile shellfish losses are significant.

Projecting the economic consequences of ocean acidification's impact on entire ecosystems is difficult because biological responses are not known for most species. We need to understand how finfish populations will respond in the future to possible larval damage, shifts in prey species and distributions, and coral reef habitat loss. Humans play an integral role in shaping marine ecosystems through commercial fishing methods and harvest levels, but the long-term value of these ecosystems depends on more than just the quantity of fish caught in each season. Degraded marine resources affect humans through a variety of environmental connections. Coral loss will expose low-lying coastline communities and diverse mangrove ecosystems to storm and wave damage, increasing the potential for economic and social disruption following severe weather events. Many coastal and island societies in the developing world depend heavily on marine fisheries and tourism, and they stand to suffer the most economically from the consequences of ocean acidification.

IMPLICATIONS FOR U.S. POLICY AND MANAGEMENT

Until ocean acidification can be mitigated through a global reorganization of the energy and transportation infrastructure, initial responses must target local and regional scales. Action items that would work to maintain sustainable marine resources include: 1) updating fishery management plans to anticipate acidification; 2) adopting ecosystem-based management plans; 3) identifying ecologically resilient areas; and 4) planning for the social and economic consequences of ocean acidification. These efforts do not require large amounts of capital and can be tailored regionally.

Research into ocean acidification's impacts on all life stages (larval, juvenile, adult) of vulnerable marine life is also essential and will allow fisheries to be managed holistically by incorporating species interactions, predator-prey relationships, and the effects of changing ocean chemistry. Fishery management models that include acidification and climate change parameters will help determine appropriate future harvest levels for many fisheries. The likelihood that complex secondary ecological effects will follow species-specific responses emphasizes the need for ecosystem-based management. Ecosystem-scale planning will be particularly useful in areas where fisheries are dominated by predatory finfish (e.g., U.S. Pacific regions). These areas will be particularly vulnerable to changes in keystone/prey species and benthic habitat degradation, which could multiply the net negative effects of acidification.

Implementation of ecosystem-based fishery management and conservation of non-commercial species will allow greater numbers of species to survive changes in ocean chemistry and the ensuing ecological shifts that are likely to occur. A reduction in fishing pressure and preventable environmental stressors (such as local pollution) should begin before ocean acidification's effects on marine resources become obvious. The consequences of a precautionary approach to fishery management could decrease revenues in the short term, but may in fact result in greater fish stocks and higher revenues over the long term. If fisheries are to be sustainable in the face of climate change, then fishery management plans must include indirect impacts on non-commercial prey species and vulnerable benthic habitats.

Finally, changes in fishery management methods in anticipation of ocean acidification can be implemented in a way that balances ecosystem and social objectives by decreasing some catches and increasing others. Catch reductions may require temporary, regional, or permanent fishery closures in some areas. To maintain economic well-being in marine-resource-dependent communities during such a transition, managers can buy back fishing licenses and gear and provide job training. Increasing fishery capacity might involve encouraging multi-species fishing, developing new markets, minimizing waste, increasing aquaculture, or supporting research to select for species or strains that are less sensitive to altered seawater chemistry (Charles 2007). Mitigating the local economic effects of such a change will require temporary economic support to displaced individuals through re-education and job transitions.

A GLOBAL CHANGE WITH HUMAN CONSEQUENCES

Ocean acidification is a worldwide problem that is poised to affect multiple levels of society through our relationships with the marine environment. Dramatic declines in calcifying organisms and the commercially important species that feed on them are likely to accompany acidification, with substantial direct ecological and economic losses. Less clear are the indirect economic and social consequences of ocean acidification's effects on food webs and marine habitats. Middlemen, retailers, and consumers are all likely to experience secondary losses; the ways in which these groups experience and respond to ocean acidification will partly dictate the total economic and social costs to humans.

Policy changes designed to support marine conservation efforts in the face of ocean acidification must be initiated as soon as possible. Because of time lags in Earth's carbon system, the CO_2 that has already been released will continue to alter ocean chemistry throughout the foreseeable future. Earth has been slow to recover from past perturbations in the carbon system, and the biological changes associated with present-day ocean acidification will become more and more apparent over the coming decades. Economic effects of changing seawater chemistry will compound over time, beginning with losses of single species and culminating in entire ecosystem shifts. Reducing CO_2 emissions over the next few decades, despite the possibility of small up-front costs, could provide noticeable economic benefits over the next several generations.

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RESOURCES

National Marine Fisheries Service commercial fishing statistics: **http://www.st.nmfs.noaa.gov/st1/index.html**

PHOTO CREDITS

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Figure 2: Courtesy of Dr. John Guinotte

Figure 3: Courtesy of NOAA's Undersea Research Program/ Office of Oceanic and Atmospheric Research

Figure 4: Courtesy of Arctic Climate Impacts Assessment (ACIA), *Impacts of a Warming Arctic: Arctic Climate Impact Assessment*. Cambridge University Press, 2007.

Table 2: Adapted from Fabry et al. 2008