ENVIRONMENTAL RESEARCH
LETTERS

Anticipating ocean acidification’s economic consequences for commercial fisheries

To cite this article: Sarah R Cooley and Scott C Doney 2009 *Environ. Res. Lett.* **4** 024007

IOP PUBLISHING ENVIRONMENTAL RESEARCH LETTERS
Environ. Res. Lett. **4** (2009) 024007 (8pp) doi:10.1088/1748-9326/4/2/024007

Anticipating ocean acidification's economic consequences for commercial fisheries

Sarah R Cooley[1] **and Scott C Doney**

Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA

E-mail: scooley@whoi.edu

Received 14 January 2009
Accepted for publication 8 May 2009
Published 1 June 2009
Online at stacks.iop.org/ERL/4/024007

Abstract
Ocean acidification, a consequence of rising anthropogenic CO_2 emissions, is poised to change marine ecosystems profoundly by increasing dissolved CO_2 and decreasing ocean pH, carbonate ion concentration, and calcium carbonate mineral saturation state worldwide. These conditions hinder growth of calcium carbonate shells and skeletons by many marine plants and animals. The first direct impact on humans may be through declining harvests and fishery revenues from shellfish, their predators, and coral reef habitats. In a case study of US commercial fishery revenues, we begin to constrain the economic effects of ocean acidification over the next 50 years using atmospheric CO_2 trajectories and laboratory studies of its effects, focusing especially on mollusks. In 2007, the \$3.8 billion US annual domestic ex-vessel commercial harvest ultimately contributed \$34 billion to the US gross national product. Mollusks contributed 19%, or \$748 million, of the ex-vessel revenues that year. Substantial revenue declines, job losses, and indirect economic costs may occur if ocean acidification broadly damages marine habitats, alters marine resource availability, and disrupts other ecosystem services. We review the implications for marine resource management and propose possible adaptation strategies designed to support fisheries and marine-resource-dependent communities, many of which already possess little economic resilience.

Keywords: ocean acidification, commercial fisheries, economic assessment, management implications

1. Introduction

Intensive fossil-fuel burning and deforestation over the last two centuries have increased atmospheric CO_2 by almost 40% above preindustrial values to levels higher than at any time over the past 800 000 years or longer (Doney and Schimel 2007). Future projections suggest even more rapid CO_2 accumulation unless dramatic actions are taken to curb human CO_2 emissions. The global ocean currently absorbs ~30% of the released anthropogenic CO_2 (Sabine *et al* 2004, Denman *et al* 2007), fundamentally altering ocean chemistry by acidifying surface waters (Caldeira and Wickett 2003) and shrinking ocean regions hospitable to calcium carbonate ($CaCO_3$) shells and skeletons (Orr *et al* 2005, Feely *et al* 2008). Ongoing ocean acidification thus may harm a wide range of marine organisms and the food webs that depend on them, thereby degrading entire marine ecosystems (Fabry *et al* 2008, Doney *et al* 2009). Laboratory studies suggest that mollusks, including species that support valuable marine fisheries such as mussels and oysters (Gazeau *et al* 2007), and especially their juveniles (Kurihara *et al* 2007, 2009, Cohen 2008, Barton 2009), are particularly sensitive to these changes. Societies dependent on marine calcifiers could consequently experience significant economic losses and even social disruptions over the next several decades. In this study, we begin to constrain the potential economic effects

---

[1] Address for correspondence: Woods Hole Oceanographic Institution, Clark, MS #25 Woods Hole, MA 02543, USA.

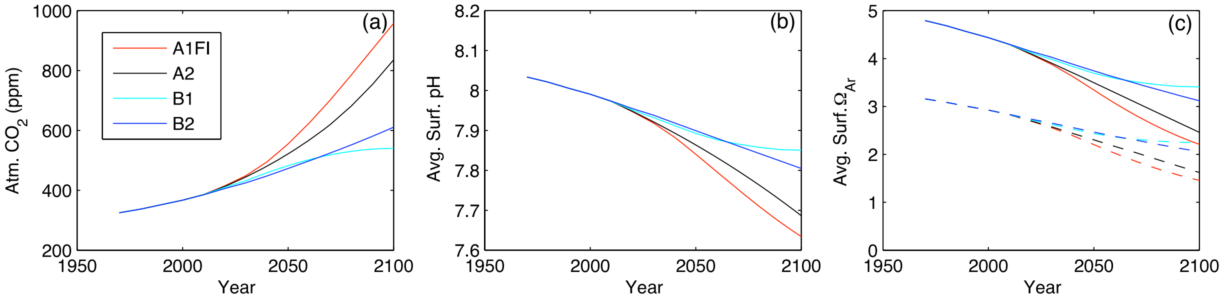

Figure 1. (a) Atmospheric CO_2 anticipated for a variety of scenarios from the Intergovernmental Panel on Climate Change's (IPCC's) Special Report on Emissions Scenarios (SRES): pathways B1, B2, A2, and intensive fossil-fuel dependence pathway A1FI, calculated with the Bern-CC model reference case (IPCC 2001). Surface ocean (b) pH and (c) calcium carbonate saturation state Ω (for calcite, solid; for aragonite, dashed) for each scenario calculated assuming constant temperature, salinity, and total alkalinity.

of ocean acidification using US commercial fishery revenues from 2007 as a case study, focusing especially on mollusks. We also identify implications for marine resource management and review possible adaptation strategies designed to support fisheries and marine-resource-dependent communities.

2. Ocean acidification and marine organisms

The oceanic uptake of anthropogenic CO_2 occurs through a series of well-known chemical reactions that increase aqueous CO_2, lower seawater pH, and lower carbonate ion levels. To date, anthropogenic CO_2 has reduced average surface ocean pH to 8.1 from a preindustrial value of 8.2, a 30% increase in acidity (Caldeira and Wickett 2003). Equally important for marine life, acidification decreases carbonate concentration and thus the saturation state of $CaCO_3$ minerals in the upper ocean (Ω). The projected increase in anthropogenic CO_2 emissions over the next 50 years, primarily associated with industrial growth in developing nations, will accelerate ocean chemistry changes to rates unprecedented in the recent geological record (figure 1; Doney *et al* 2009, Doney and Schimel 2007). Model-predicted atmospheric CO_2 trajectories increase from ∼385 ppm in 2008 to 450–650 ppm by 2060 (IPCC 2001), which would decrease average ocean surface pH by an additional 0.2–0.3 units (to an average of 7.9–7.8) and reduce the saturation states of calcite (Ω_{ca}) and aragonite (Ω_{ar}) by ∼25% (figure 1), further shrinking optimal regions for biological carbonate formation (Steinacher *et al* 2009). Seasonal acidification events are already appearing; water with $\Omega_{ar} < 1$ (undersaturated or corrosive conditions) upwells along the California coastline in summer, decades earlier than models predict (Feely *et al* 2008). Also, some high-latitude polar and subpolar waters may see $\Omega_{ar} \sim 1$ by mid-century or earlier (Orr *et al* 2005, Steinacher *et al* 2009). Worse, average forecasts may even be somewhat conservative; estimated fossil-fuel CO_2 emissions in 2005 exceeded those predicted by the most extreme scenario from the 1990s (A1FI in figure 1; Raupach *et al* 2007), implying that future atmospheric CO_2 levels may exceed current model predictions, and the oceans may acidify faster than presently forecast.

Organisms' net responses to rising CO_2 will vary depending on often opposing sensitivities to decreased seawater pH, carbonate concentration, and carbonate saturation state, and to elevated oceanic total inorganic carbon and gaseous CO_2. Shell-forming marine organisms create carbonate structures using one of two approaches. Detailed reviews can be found in Fabry *et al* (2008), Doney *et al* (2009). Briefly, organisms that exert low biological control over calcification directly deposit $CaCO_3$ along their inner shell walls, and consequently, they depend on a sufficient ambient carbonate concentration to accumulate shells successfully. Commercially valuable mollusks such as bivalves (e.g., scallops, oysters) and some gastropods (e.g., conchs) use this method to build shells. Shells deposited in this manner are more likely to contain aragonite, a more soluble mineral form of $CaCO_3$. Corals form aragonite skeletons extracellularly, while coralline algae secrete aragonite or magnesian calcite, a moderately soluble form of $CaCO_3$. Organisms that exert high biological control over calcification typically accumulate intracellular stocks of carbonate ions gradually and harden their chitin and protein exoskeletons by depositing $CaCO_3$ from within, usually in the less soluble form of calcite. Sea urchins and crustaceans, including lobsters, shrimp, and crabs, follow this model and therefore require less specific seawater chemistry to form shells. Animals' ultimate responses may also depend on less easily quantified factors such as individual history or genetic variability (Doney *et al* 2009).

Ocean acidification and declining carbonate concentration could directly damage organisms, specifically corals and mollusks, by decreasing calcification rates. Reduced calcification is observed in response to rising CO_2 and declining carbonate concentration even in waters that are thermodynamically supersaturated for calcium carbonate (Ω decreasing but still above 1). Many organisms, some commercially valuable, also exhibit a range of negative consequences for metabolism, reproduction, development, intracellular chemistry, and immunity (e.g., Fabry *et al* 2008, Holman *et al* 2004, Burgents *et al* 2005, and references therein) (table 1). Acidification's effects on fishes' ability to grow internal carbonate structures for feeding and migration such as otoliths, statoliths, and gastroliths are still unknown. On the other hand, some planktonic organisms, crabs, lobsters, shrimp, and other organisms increase calcification or photosynthesis in high-CO_2 seawater (Ries *et al* 2008a, 2008b, Doney *et al* 2009). Whether the observed examples

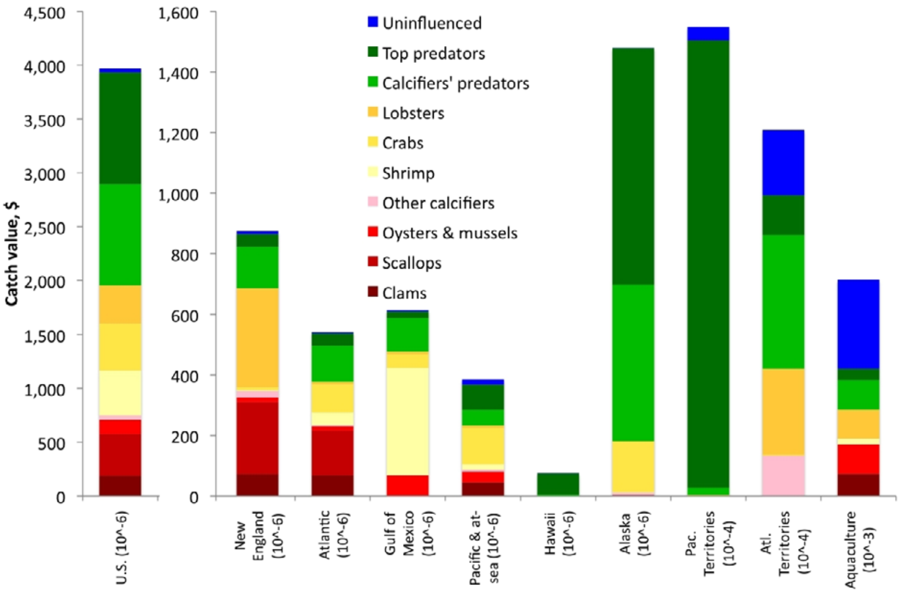

Figure 2. US commercial fishing ex-vessel revenue for 2007 (NMFS statistics, accessed October 2008). Reds indicate organisms containing primarily aragonite, yellows indicate those using primarily calcite, greens indicate predators, and blue indicates species not directly influenced by ocean acidification. (NMFS statistics and Andrews *et al* 2008.)

Table 1. Responses of some commercially important species to laboratory ocean acidification experiments, adapted from Fabry *et al* (2008).

Category	Species	pH	CO_2	Shell dissol	Incr. mortality	Other
Mussel	*M. edulis*	7.1	740 ppm	Y	Y	25% decrease in calcification rate
Oyster	*C. gigas*		740 ppm			10% decrease in calcification rate
Giant scallop	*P. magellanicus*	<8.0				Decrease in fertilization, development
Clam	*M. mercenaria*	7.0–7.2		Y	Y	$\Omega_{ar} = 0.3$
Crab	*C. pagurus*	10 000 ppm				Reduced thermal tolerance
Crab	*N. puber*	7.98–6.04	0.08–6.04 kPa	Y		Intracellular acid/base disruption
Sea urchin	*S. purpuratus*	6.2–7.3		Y		Lack of pH regulation
Dogfish	*S. canicula*	7.7			Y	
Sea bass	*D. labrax*	7.25				Reduced feeding

of increased calcification or photosynthesis under high-CO_2 conditions result in enhanced species fitness is not yet known. But decreases in calcification and biological function seem very capable of decreasing fitness of commercially valuable groups, like mollusks, by compromising early development and survival (e.g., Kurihara *et al* 2007, 2009) or by directly damaging shells (e.g. Gazeau *et al* 2007).

Ocean acidification's total effects on the marine environment will depend also on ecosystem responses. Even if carbonate-forming organisms can form shells and skeletons in elevated-CO_2 conditions, they may pay a high energetic cost (Wood *et al* 2008) that could reduce survival and reproduction (Kleypas *et al* 2006). Losses of plankton, juvenile shellfish, and other prey also would alter or remove trophic pathways and intensify competition among predators for food (Richardson and Schoeman 2004), potentially reducing harvests of economically important predators. At the same time, acidic conditions will damage coral and prevent its regrowth, destroying crucial benthic habitats and disrupting hunting and reproduction of an array of species (Kleypas *et al* 2006, Lumsden *et al* 2007). Ecological shifts to macroalgal overgrowth and decreased species diversity sometimes follow after coral disturbances (Norström *et al* 2009), creating stable new ecosystem states (Scheffer *et al* 2001) dominated by herbivores (Hoegh-Guldberg *et al* 2007) and less commercially valuable species. Ocean acidification has been implicated in similar ecological shifts from calcifying organisms to seagrasses and algae in wild benthic communities with decreasing pH (Hall-Spencer *et al* 2008, Wootton *et al* 2008).

3. Economic consequences for US commercial fisheries

Ocean acidification may affect humans through a variety of socio-economic connections, potentially beginning with reduced harvests of commercially important species. The total ex-vessel or primary value of US commercial harvests from US waters and at-sea processing was nearly $4 billion in 2007 (all monetary values given in US dollars) (figure 2; NMFS statistics, http://www.st.nmfs.noaa.gov/st1/index.html, and Andrews *et al* 2008). Of the total, mollusks provided 19% (red tones), crustaceans yielded 30% (yellows), and finfish generated 50% (greens); 24% of total US ex-vessel revenue

Table 2. Revenues from US recreational (2000, Steinback *et al* 2004) and commercial (2007, Andrews *et al* 2008) fishing.

Recreational	
Total economic impact[a]	$ 42 868 million
Jobs supported	349 119
Commercial	
Domestic ex-vessel revenue	$ 3765 million
+Harvest outside US	$ 159 million
+Aquaculture	$ 1244 million
Primary sales	$ 5168 million
Retail sales	$ 68 390 million
GNP contribution	$ 34 159 million

[a] Economic impact encompasses jobs, revenue, and income. Numbers exclude Texas, Alaska, and Hawaii; see Steinback *et al* (2004) for details.

was from harvesting fish that prey directly on calcifiers. The supplementary information lists the NMFS-tracked species included in each category. Different groups dominate regional revenues; mollusks are more important in the New England and mid to south Atlantic regions (figure 2), crustaceans contribute greatly to New England and Gulf of Mexico fisheries, and predators dominate the Alaskan, Hawaiian, and Pacific-territory fisheries.

Nationwide, income and jobs generated by US fisheries multiply dramatically from catch to retail sale. In 2007, domestic commercial fisheries, harvest from outside US territories, and aquaculture provided a primary sale value of \$5.1 billion (table 2; all dollar values in this paper are in 2007 dollars unless otherwise indicated). Processing, wholesale, and retail activities led to sales of \$68.3 billion, contributing \$34.2 billion in value added to the US gross national product in 2007 (Andrews *et al* 2008). The number of individuals employed directly and indirectly by commercial fishing is difficult to quantify, because fishermen are frequently self-employed; furthermore, middlemen who do not handle solely ocean products are not counted in industry surveys. In the United States, commercial fish processing and wholesaling together supported 63 000 jobs in 2007 (Andrews *et al* 2008). For perspective, in 1999, commercial fishing employed 10 500 people in New York State, wholesale and processing supported 5060 jobs, and retail sales supported an additional 10 100 jobs. Seafood sales at New York restaurants supported the equivalent of 70 000 full-time jobs. In total, the seafood industry supported nearly 100 000 jobs in New York State (New York Sea Grant 2001).

Supplementing the economic benefit from commercial fishing, US recreational fishing encourages spending on permits, equipment, and travel, and in support industries, thereby generating jobs, profits, tax revenues, and business-to-business revenue. In 2000 (the latest date for which data is available), recreational saltwater fishing generated \$12 billion of income in the United States (Steinback *et al* 2004) and supported almost 350 000 jobs, for a total economic benefit of \$43 billion that year (table 2).

Ocean acidification's impact is not yet known for every commercially and recreationally valuable species, but emerging data suggest that the number or quality of many high-value, aragonite-forming mollusks could decrease, and declining economic revenues in that fishery sector may follow. This possibility is supported by findings such as decreased mollusk populations in acidified ecosystems (Wootton *et al* 2008, Hall-Spencer *et al* 2008), malformation of juvenile oyster shells in aragonite-undersaturated laboratory studies (Cohen 2008), and decreased survival of oyster larvae in upwelling Oregon seawater with decreased pH and altered biogeochemistry (Barton 2009). Mollusks and crustaceans comprise the bottom or middle trophic levels of many ecosystems, implying that acidification-related damage to either of these groups also may negatively impact their primary and secondary predators (Fredriksen *et al* 2007, Richardson and Schoeman 2004). Effects of prey losses on predator numbers are poorly quantified at present, however, and the total ecosystem impact will depend on whether alternative prey species are available and whether predators can switch among prey. Currently, predictions of ex-vessel losses from declining mollusk harvests must depend on translating laboratory experiments showing damage to individual organisms into population losses in nature. To our knowledge, there have been no experimental results published in the literature to date that quantitatively link calcification decreases or organism mortality to decreasing saturation state in a natural environment. Nevertheless, existing data do permit estimating potential first-order losses associated with ocean acidification.

To provide a starting point for discussing ocean acidification's economic impact on mollusks, we assume a simple one-to-one correspondence between reduced calcification for a particular atmospheric CO_2 level and reduced commercial mollusk harvests. We construct future harvest trends using IPCC atmospheric CO_2 trajectories and the laboratory results of Gazeau *et al* (2007), who observed 10–25% decreases in mollusk calcification rates at $CO_2 \sim 700$ ppm (pH $\sim$ 7.9–8.0, $\Omega_{ar} \sim 2$, and $\Omega_{ca} \sim 3$). Atmospheric CO_2 of 700 ppm occurs by 2060 in a high-CO_2 emissions world (A1FI; figure 1) and after 2100 in a low-CO_2 emissions world (B1). This assumed relationship, although certainly imperfect and preliminary, generates results broadly consistent with the limited available field data. Here, harvest decreases of 6%–25% (B1, low rate–A1FI, high rate) accompany 0.1–0.2-unit pH decreases over 50 years (2010–2060), whereas Wootton *et al* (2008) observed a 10%–40% decrease in calcifying organism cover associated with a 0.4-unit pH decrease over just 8 years in a natural coastal lagoon environment.

As is clear from the temporal mismatch between our model and field observations, our assumptions cannot completely address the complexity that will dictate ocean acidification's total economic effects. We assume no regional variations in acidification, and we neglect potentially significant changes in commercial fishing from consequences for crustaceans, trophic cascade changes involving predators and finfish, finfish larvae damage, or coral reef habitat losses. By highlighting just mollusk fisheries, our projections may in fact underestimate fisheries impacts if the effects of acidification occur more broadly across ecosystems. These

Table 3. Time-integrated net present values (NPV) by 2060 of economic losses, assuming declining mollusk catches associated with IPCC B1 or A1FI emissions scenarios, and the time-integrated NPV of US and regional fisheries by 2060, assuming no catch decreases. NPVs are in millions (US 2007 dollars). The bottom row shows economic losses as per cent of fishery NPV. The low (high) end of each calculated range corresponds to calcification decreases resulting in 10% (25%) mollusk harvest losses by the time $\Omega_{ar} \sim 2$ or ~700 ppm CO_2.

Emission scenario	Low IPCC Atm. CO_2 (B1)			High IPCC Atm. CO_2 (A1FI)			Integrated NPV of fishery; no catch decreases from acidification		
Net discount rate	4%	2%	0%	4%	2%	0%	4%	2%	0%
US	324–809	610–1523	1226–3063	543–1358	1023–2557	2058–5144	17 115	25 063	40 406
New Bedford, MA	116–290	218–546	439–1097	195–486	366–916	737–1843	6130	8977	14 472
New England	150–375	283–706	569–1421	252–630	474–1186	954–2385	7936	11 622	18 737
Pacific	38–94	71–177	143–357	63–158	119–298	240–599	1994	2920	4708
% loss from fishery NPV	1.9–4.7	2.4–6.1	3.0–7.6	3.2–7.9	4.1–10.2	5.1–12.7			

ecosystem-scale responses are outside the scope of this study, yet are expected to greatly shape outcomes by guiding individual species responses; Wootton *et al* (2008) note that the significant community shift they observed was likely a function of multiple ecosystem factors and not just declining calcification or organism health. Furthermore, biological studies have not yet quantitatively identified ameliorative long-term processes that could offset losses, like natural selection of resistant species or strains, or initiation of self-defensive strategies. For the economic projections, we also make no assumptions about changes in fishing intensity or the effects of supply and demand on marine resource prices.

Here, we calculate potential revenue losses from decreased mollusk harvests in the future, adjust to present-day values using a range of net discount rates (0%, 2% and 4%), and integrate over time to provide estimates of net present value (NPV); anticipated future revenue losses are worth less than losses today because of the compounding effects of interest and capital return rates. Mollusks accounted for $748 million (19%) of 2007 US domestic ex-vessel revenues, with an NPV (assuming no changes from present ecological and economic conditions from today) integrated to mid-century (2007–2060) of roughly $17–40 billion depending on the applied discount rate. If just a 10–25% decrease in US mollusk harvests from 2007 level were to occur today, $75–187 million in direct revenue would be lost each year henceforth, with a net NPV loss of $1.7–10 billion through mid-century.

A more realistic scenario would involve more gradual annual revenue declines with increasing atmospheric CO_2 and acidification. Table 3 provides estimates of the NPV of revenue losses for the US mollusk fishery through 2060 for varying discount rates, high-CO_2 and low-CO_2 atmospheric trajectories, and the upper/lower bounds from Gazeau *et al* (2007) experiments to constrain the range of biological responses (−10% to −25% for $\Omega_{ar} \sim 2$ or ~700 ppm CO_2). For a moderate net discount rate of 2%, the NPV of US ex-vessel revenue losses are substantial: $0.6–2.6 billion through 2060. The NPV or revenue loss is also sensitive to future atmospheric CO_2 trajectories and thus to decisions about CO_2 emissions; the high-CO_2 scenario losses are almost 1.7 times larger than those for the low-CO_2 scenario, and this factor continues to grow with longer time horizons. These revenue losses would be unevenly distributed, being nearly four times higher in mollusk-dependent New England than in the Pacific.

The broader economic effects of reduced mollusk harvests due to ocean acidification are more difficult to quantify, but we may be able to illustrate the potential effects through some simple economic comparisons and calculations. Economic losses from harmful algal blooms (HABs), whose damage to lower trophic levels and cascading economic consequences may resemble those of ocean acidification, cost the United States an average of $12 million each year (in 2000 dollars) by causing human sickness, fish mortality, decreased demand for fish products, habitat loss, damage to fisheries valuable in the future, and depressed recreation and tourism (Hoagland *et al* 2002). In certain well-studied markets, broader shellfish economic losses resulting from HABs have been estimated with an economic multiplier of 2.0–3.0 (Hoagland *et al* 2002). Multiplying the NPV of declining mollusk ex-vessel revenues associated with ocean acidification estimated above by an intermediate value of 2.5 indicates that the time-integrated NPV of ocean acidification's broader economic losses for the United States would range from $1.5–6.4 billion through 2060 for a 2% discount. However, the magnitude of economic multipliers may change in the future if market conditions vary significantly from those used to develop the multiplier (Hoagland *et al* 2002); net present value also neglects the effects of supply and demand on marine resources. Fishery losses due to ocean acidification will drive job losses in affiliated industries through economic linkages that are also difficult to quantify.

Uncertainties in biological responses to ocean acidification also contribute to the range of anticipated economic impacts. Calcification rates of some calcifiers, like corals, decrease much more dramatically than those reported by Gazeau *et al* (2007) for oysters and mussels, causing noticeable degradation at lower CO_2 levels than assumed above; populations or ecosystems may also exhibit collapses or shifts above a CO_2 threshold rather than undergo a slow decline (e.g., Norström *et al* 2009). Alternatively, our calculations may be overestimates if species can adapt to gradual change (Boyd *et al* 2008) and commercial harvests shift to more abundant or acidification-resistant species over time. Studies of ecological shifts on perturbed coral reefs, for example, suggest that herbivorous species like parrotfish (e.g., Hoegh-Guldberg *et al* 2007) may thrive in future non-coral-dominated reef communities. Currently the US commercial market for parrotfish is quite small—in 2007 ex-vessel revenues were only \$161 000 (NMFS statistics)—but future abundance does not necessarily imply increased market interest. Refining economic loss estimates depends on better understanding marine responses to ocean acidification, accounting for adaptation or conservation measures enacted in the next 50 years, and correctly predicting market responses to fishing changes (Hoagland *et al* 2002).

Secondary economic losses following decreased fishery harvests will be concentrated in specific regions, many of which have less economic resilience for enduring losses of fishing revenues. For example, New Bedford, MA, has historically relied on fishing income and currently hosts a large scallop fleet. In 2007, its mollusk-dominated ex-vessel revenues were \$268 million, making New Bedford the top American port in terms of landing revenues (NMFS statistics). A 25% loss from ocean acidification would decrease landing revenues by \$67 million a year or cause an NPV loss of \$2.2 billion through 2060 (2% net discount); the more conservative acidification scenario presented above would result in an NPV of direct revenue losses of \$546–916 million (table 3), followed by spiraling costs associated with indirect socio-economic losses. Already, the seafood products employment sector in New Bedford decreased 25% from 1992–1999; fishing-related declines also affect wholesale, some retail sales, and transportation (Center for Policy Analysis 2001). Certainly, any economic losses could harm this region, where 20% of the population in 1999 fell below the poverty line (compared to 9% statewide and 11% nationwide that year; US Census data) and where the income gap separating the highest- and lowest-income families is growing at the sixth fastest rate nationwide (Gittell and Rudokas 2007a, 2007b, Center for Policy Analysis 2001). Economic changes resulting from fishery losses in a city like New Bedford could continue to alter its dominant economic activities and demographics, and further accelerate the income gap's development.

4. Management implications

The only true solution or mitigation option for ocean acidification is limiting fossil-fuel CO_2 emissions to the atmosphere (Pacala and Socolow 2004), a long-term goal that requires a fundamental reorganization of energy and transportation infrastructures worldwide. Climate geoengineering approaches that do not control atmospheric CO_2 will not address acidification (Zeebe *et al* 2008). Because ocean acidification's seawater chemistry changes are already apparent and will grow over the next few decades (e.g., Feely *et al* 2008), short-term responses intended to conserve sustainable marine environmental resources should also focus on adaptation to the inevitable near-future CO_2 increases. Addressing the global problem of ocean acidification with the goal of preserving commercially valuable fisheries resources will require regional solutions. Some local-scale strategies, like enhanced electrochemical weathering (House *et al* 2007), directly combat seawater ocean acidification by increasing alkalinity, but such methods would likely be expensive and energy intensive for a small benefit. Other strategies, like updating fishery management plans to include acidification, are less costly and can be regionally tailored as needed to accommodate biological, economic, and social variations.

Designing new policies must begin with comprehensive research targeted towards regional needs (Doney *et al* 2009). First, expanded time series studies of coastal and open-ocean seawater chemistry are needed to monitor ocean acidification's progress and place it in context with historical data. Second, basic studies at the organism level are required to enhance our currently limited knowledge of commercial and keystone species' responses to decreased pH and elevated CO_2. Topics of particular interest include the roles that life history and population variability may play in shaping acidification responses and the sensitivity of mollusk, crustacean, and finfish larvae, juveniles, and adults to changing seawater chemistry. Third, ecosystem-wide studies are needed to shed light on secondary effects from habitat and prey losses; such information will be particularly useful for fisheries dominated by predatory finfish, like the US Pacific regions, where the relative effects of prey switching, keystone species change, benthic and habitat degradations, and overall biomass reduction must be understood for long-term planning. Biological research results will enable managers to identify and aid regionally valuable species better; for example, research might suggest adjustments to fishery quotas or marine protected areas, show that aquaculture of juvenile mollusks is warranted along some coastlines, or that preservation of a particular keystone predator would keep some crustacean fisheries robust. Fourth, economic and social science studies are needed to understand better how markets, prices, and communities will respond to declining fishery harvests and how best to mitigate potential socio-economic impacts.

For improved long-range planning, quantitative assessments of marine organisms' responses to ocean acidification and climate change must be explicitly incorporated into fishery management plans. Mathematical fisheries models should be enhanced with chemistry and temperature-driven climate change and acidification terms, based on species-specific observational studies, to help determine appropriate harvest levels for many fisheries. Such model refinement would help ensure that catch levels remain sustainable despite ongoing environmental changes. However, the likelihood of complex secondary effects resulting from ocean acidification emphasizes the need for developing and using ecosystem-based management models. More accurate predictions of ocean acidification's regional economic effects would arise from bioeconomic models adjusted for ocean acidification and climate change, enabling timely implementation of fiscally sound responses.

Fishery management and conservation should also enable sufficient proportions of non-commercial species to survive changing ocean chemistry and any ensuing ecological shifts so that fundamental ecosystem function and services are preserved (Costanza *et al* 1997). Following a precautionary approach to management, fishing pressure reduction and environmental stress minimization should therefore begin before ocean acidification's effects on marine resources become obvious and perhaps irreversible. The consequences of a precautionary approach could decrease fishery revenues in the short term, but such a conservation strategy may in fact result in greater fish stocks and higher revenues in the long run when economic discounting and sustainable yields are included (Costanza *et al* 1997). Adjusting fishery management plans must take into account not only economic considerations, but also biological or conservation goals and social outcomes, like community preservation (Charles 2007).

An 'objectives-based' approach to addressing ocean acidification can help balance both ecosystem and social objectives through adjusting fishing pressure (Charles 2007). Decreasing fishery capacity by reducing external pressures and conserving the marine environment may involve license or vessel buyouts, or regional fishery closures of varying durations. Increasing fishery capacity could involve encouraging multi-species fishing, developing new markets, minimizing waste, increasing aquaculture, or supporting research to select for less pH- and Ω-sensitive species or strains. However, shifting fishing activities via these methods while avoiding widespread unemployment also requires coupled labor market adjustments such as retraining fishers and rewarding job transitions. Furthermore, social measures must be pursued to support marine-resource-dependent communities, which may experience changes in demographics, community organization, livelihoods, local economies, generational roles, and government involvement during the shift.

A particular difficulty that managers face in addressing ocean acidification is its long timescale, creating the illusion that this very urgent problem can be handled later. On the contrary, the slow recovery of the earth system from rapid atmospheric CO_2 increases (Andrews *et al* 2008) means that CO_2 emissions to date will continue to alter ocean chemistry in the foreseeable future. Ocean acidification meanwhile will drive biological changes apparent over ~50 years and economic effects that will compound over time; note the potential for time-integrated NPV of ex-vessel revenue losses to increase 30–300%, depending on discount rate, from 2060 to 2100 (table 3). Reducing CO_2 emissions over the next few decades, despite incurring small up-front costs, could consequently provide noticeable economic benefits over the next several generations (Stern Review 2006).

The worldwide political, ethical, social, and economic ramifications of ocean acidification, plus its capacity to switch ecosystems to a different state following relatively small perturbations, make it a policy-relevant 'tipping element' of the earth system (Lenton *et al* 2008). Because the fate of this tipping element will be decided within the century, policies should address ocean acidification quite soon. Complicating the development of comprehensive responses is the intermediate timescale over which ocean acidification operates: longer than multiyear adaptive fishery management plans, but shorter than decades-to-centuries CO_2 mitigation plans. The uncertainty of whether ocean acidification's effects will appear incrementally or after dramatic ecosystem reorganizations also hinders planning. Despite these drawbacks, regional-scale marine resource management plans must begin now to estimate the scope of ocean acidification's consequences, and these short-term efforts must be followed by long-term CO_2 mitigation plans to continue progress.

The present assessment only focuses on the United States and excludes economic consequences for coral ecosystems (see treatments in, e.g., Cesar *et al* 2002, Burke *et al* 2004), but the effects of ocean acidification will be global. Marine resources are important food supplies that provide 20% of the world's protein (FAO 2007), distributed unevenly around the world. Some developing island and coastal nations that depend heavily on marine and coral ecosystems for food, tourism, and exportable natural resources stand to suffer the most economically (Stern Review 2006) from the consequences of ocean acidification and climate change. As rising sea levels physically endanger these communities, ocean acidification may decrease their food supplies. Additionally, coral damage 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. Fortunately, the chemistry of ocean acidification is predictable, which allows us to anticipate its effects and enact management plans that will protect the United States' economic interests and provide strategies helpful for other nations.

Acknowledgments

We thank P Hoagland, D Jin, and H Kite-Powell for helpful discussions, and we are grateful for the insightful suggestions of J Guinotte, E Miles, A Murawski, A Solow, and an anonymous reviewer. This work was supported by NSF grant ATM-0628582.

References

Andrews R *et al* 2008 Fisheries of the United States 2007 *Current Fishery Statistics No. 2007* National Marine Fisheries Service, Office of Science and Technology

Barton A 2009 personal communication

Boyd P W *et al* 2008 Climate-mediated changes to mixed-layer properties in the Southern Ocean: assessing the phytoplankton response *Biogeosciences* **5** 847–64

Burgents J E, Burnett K G and Burnett L E 2005 Effects of hypoxia and hypercapnic hypoxia on the localization and the elimination of *Vibrio campbelli* in *Litopenaeus vannamei*, the Pacific white shrimp *Biol. Bull.* **208** 159–68

Burke L *et al* 2004 *Reefs at Risk in the Caribbean* World Resources Institute, Washington, DC http://www.wri.org/publication/reefs-risk-caribbean

Caldeira K and Wickett M E 2003 Anthropogenic carbon and ocean pH *Nature* **425** 365

Center for Policy Analysis 2001 *Greater New Bedford Economic Base Analysis: Critical and Emerging Industries and Workforce Development Targets* (*Economic Research Series* no 29) University of Massachusetts Dartmouth

Cesar H, van Beukering P, Pintz S and Dierking J 2002 Economic valuation of the coral reefs of Hawaii *Report of the Hawaii Coral Reef Initiative NOAA* http://marineeconomics.noaa.gov/Reefs/hcri1.html

Charles A 2007 The human dimension of fisheries adjustment: key issues and policy challenges *Structural Change in Fisheries:*

Dealing with the Human Dimension (Paris: Organisation for Economic Co-operation and Development) pp 15–44

Cohen A 2008 personal communication

Costanza R *et al* 1997 The value of the world's ecosystem services and natural capital *Nature* **387** 253–60

Denman K L *et al* 2007 Couplings between changes in the climate system and biogeochemistry *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed S Solomon *et al* (Cambridge: Cambridge University Press)

Doney S C, Fabry V J, Feely R A and Kleypas J A 2009 Ocean acidification: the other CO_2 problem *Annu. Rev. Mar. Sci.* **1** 169–92

Doney S C and Schimel D S 2007 Carbon and climate system coupling on timescales from the Precambrian to the Anthropocene *Annu. Rev. Environ. Res.* **32** 31–66

Fabry V J, Seibel B A, Feely R A and Orr J C 2008 Impacts of ocean acidification on marine fauna and ecosystem processes *ICES J. Mar. Sci.* **65** 414–32

Feely R A, Sabine C L, Hernandez-Ayon J M, Ianson D and Hales B 2008 Evidence for upwelling of corrosive 'acidified' water onto the continental shelf *Science* **320** 1490–2

Food and Agriculture Organization of the United Nations 2007 *The State of World Fisheries and Aquaculture, 2006* Food and Agriculture Organization Fisheries and Aquaculture Department, Rome

Fredriksen M, Furness R W and Wanless S 2007 Regional variation in the role of bottom-up and top-down processes in controlling sandeel abundance in the North Sea *Mar. Ecol. Prog. Ser.* **337** 279–86

Gazeau F *et al* 2007 Impact of elevated CO_2 on shellfish calcification *Geophys. Res. Lett.* **34** L07603

Gittell R and Rudokas J 2007a Changes in income distribution in New England *Communities and Banking* (Fall) 20–3

Gittell R and Rudokas J 2007b New England has the highest increase in income disparity in the nation *Technical Report 4* Carsey Institute

Hall-Spencer J M *et al* 2008 Volcanic carbon dioxide vents show ecosystem effects of ocean acidification *Nature* **454** 96–9

Hoagland P, Anderson D M, Kaoru Y and White A W 2002 The economic effects of harmful algal blooms in the United States: estimates, assessment issues, and information needs *Estuaries* **25** 819–37

Hoegh-Guldberg O *et al* 2007 Coral reefs under rapid climate change and ocean acidification *Science* **318** 1737–42

Holman J D, Burnett K G and Burnett L E 2004 Effects of hypercapnic hypoxia on the clearance of *Vibrio campbelli* in the Atlantic blue crab, *Callinectes sapidus rathbun Biol. Bull.* **206** 188–96

House K Z, House C H, Schrag D P and Aziz M J 2007 Electrochemical acceleration of chemical weathering as an energetically feasible approach to mitigating anthropogenic climate change *Environ. Sci. Technol.* **41** 8464–70

Intergovernmental Panel on Climate Change 2001 Climate change 2001: the scientific basis *Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* ed J T Houghton *et al* (Cambridge: Cambridge University Press)

Kleypas J A *et al* 2006 Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers *A Guide for Future Research NSF, NOAA* US Geological Survey, St Petersburg, FL, 18–20 April

Kurihara H, Asai T, Kato S and Ishimatsu A 2009 Effects of elevated pCO_2 on early development in the mussel *Mytilus galloprovincialis Aquatic Biol.* **4** 225–33

Kurihara H, Kato S and Ishimatsu A 2007 Effects of increased seawater pCO_2 on early development of the oyster *Crassostrea gigas Aquatic Biol.* **1** 91–8

Lenton T M *et al* 2008 Tipping elements in the Earth's climate system *Proc. Natl Acad. Sci. USA* **105** 1786–93

Lumsden S E, Hourigan T F, Bruckner A W and Dorr G (ed) 2007 The state of deep coral ecosystems of the United States *NOAA Technical Memorandum CRCP-3* Silver Spring, Maryland

New York Sea Grant 2001 *The Economic Contribution of the Sport Fishing* Commercial Fishing and Seafood Industries to New York State NYSGI-T-01-001

Norström A V, Norström M, Lokrantz J and Folke C 2009 Alternative states on coral reefs: beyond coral–macroalgal phase shifts *Mar. Ecol. Prog. Ser.* **376** 295–306

Orr J C *et al* 2005 Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms *Nature* **437** 681–6

Pacala S and Socolow R 2004 Stabilization wedges: solving the climate problem for the next 50 years with current technologies *Science* **305** 968–72

Raupach M R *et al* 2007 Global and regional drivers of accelerating CO_2 emissions *Proc. Natl Acad. Sci. USA* **104** 10288–93

Richardson A J and Schoeman D S 2004 Climate impact on plankton ecosystems in the Northeast Atlantic *Science* **305** 1609–12

Ries J B, Cohen A L and McCorkle D C 2008a Marine biocalcifiers exhibit mixed responses to CO_2-induced ocean acidification *11th Int. Coral Reef Symp. (Ft Lauderdale, FL)* Mini-Symposium 3

Ries J B, Cohen A L and McCorkle D C 2008b The mineralogical responses of marine calcifiers to CO_2-induced ocean acidification *Eos Trans. AGU* **89** OS33E-04 Fall Meet. Suppl., Abstract

Sabine C L *et al* 2004 The oceanic sink for anthropogenic CO_2 *Science* **305** 367–71

Scheffer M, Carpenter S, Foley J A, Folke C and Walker B 2001 Catastrophic shifts in ecosystems *Nature* **413** 591–6

Steinacher M, Joos F, Frölicher T L, Plattner G-K and Doney S C 2009 Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model *Biogeosciences* **6** 515–33

Steinback S, Gentner B and Castle J 2004 The economic importance of marine angler expenditures in the United States *National Marine Fisheries Service, National Oceanographic and Atmospheric Administration* NOAA Professional Paper 2

Stern Review 2006 *The Economics of Climate Change* United Kingdom Treasury

Wood H L, Spicer J I and Widdicombe S 2008 Ocean acidification may increase calcification rates, but at a cost *Proc. R. Soc.* B **275** 1767–73

Wootton J T, Pfister C A and Forester J D 2008 Dynamic patterns and ecological impacts of declining ocean pH in a high-resolution multi-year dataset *Proc. Natl Acad. Sci. USA* **105** 18848–53

Zeebe R E, Zachos J C, Caldeira K and Tyrrell T 2008 Carbon emissions and acidification *Science* **321** 51–2