Anticipating ocean acidification's economic consequences on commercial fisheries

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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 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 U.S. 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 U.S. annual domestic ex-vessel commercial harvest ultimately contributed \$34 billion to the U.S. 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.

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, and 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; A.L. Cohen, 2007, personal communication; A. Barton, 2009, personal communication), 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 of ocean acidification using U.S. 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, and 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) and 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 exceeding 1). Many organisms, some commercially valuable, also exhibit a range of negative consequences on metabolism, reproduction, development, intracellular chemistry, and immunity (e.g., Fabry et al., 2008, Holman et al., 2004, and 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,b, Doney et al. 2009). Whether the observed examples 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 et al., 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, and 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 U.S. Commercial Fisheries

Ocean acidification may affect humans through a variety of socioeconomic connections, potentially beginning with reduced harvests of commercially important species. The total ex-vessel or primary value of U.S. commercial harvests from U.S. 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 U.S. ex-vessel revenue 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 U.S. fisheries multiply dramatically from catch to retail sale. In 2007, domestic commercial fisheries, harvest from outside U.S. 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 U.S. 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 5,060 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, U.S. 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 commercial and recreational 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, and Hall-Spencer et al., 2008), malformation of juvenile oyster shells in aragonite-undersaturated laboratory studies (A. Cohen 2008, personal communication), and decreased survival of oyster larvae in upwelling Oregon seawater with decreased pH and altered biogeochemistry (A. Barton 2009, personal communication). 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, and 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 ~700 ppm (pH ~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 on 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 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 U.S. 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 U.S. 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 U.S. 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 Ω_{ar} ~ 2 or ~700ppm CO_2). For a moderate net discount rate of 2%, the NPV of U.S. 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 U.S. 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 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 socioeconomic 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; U.S. Census data) and where the income gap separating the highest and lowest-income families is growing at the sixth fastest rate nationwide (Gittel and Rudokas 2007, and 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 electrochemical CO_2 capture and storage (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 U.S. 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 Atlantic coastlines, or that preservation of a particular keystone predator would keep Pacific 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, and 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.

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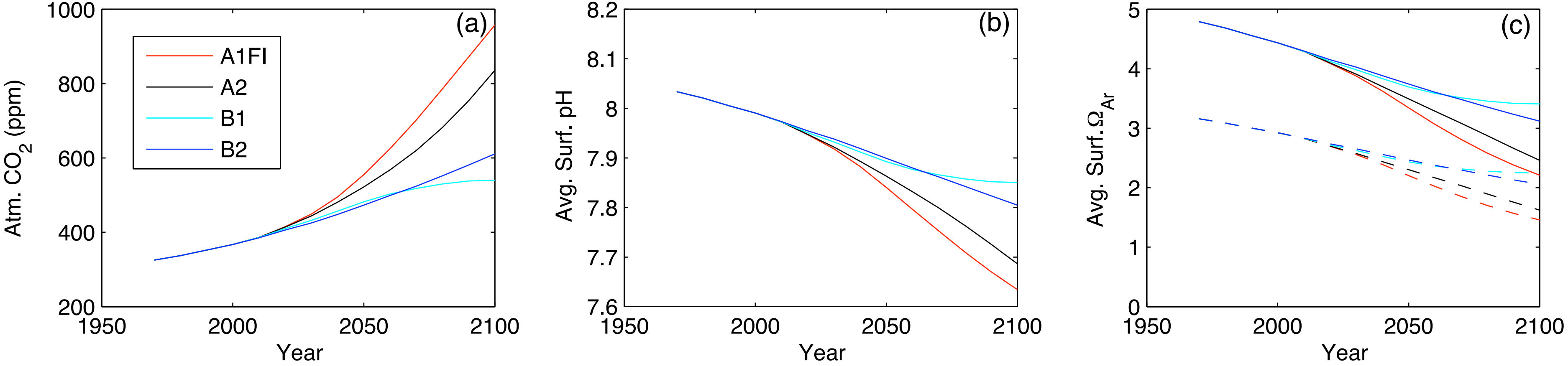
Table 1. Responses of some commercially important species to laboratory ocean acidification experiments, adapted from Fabry et al., (2008)

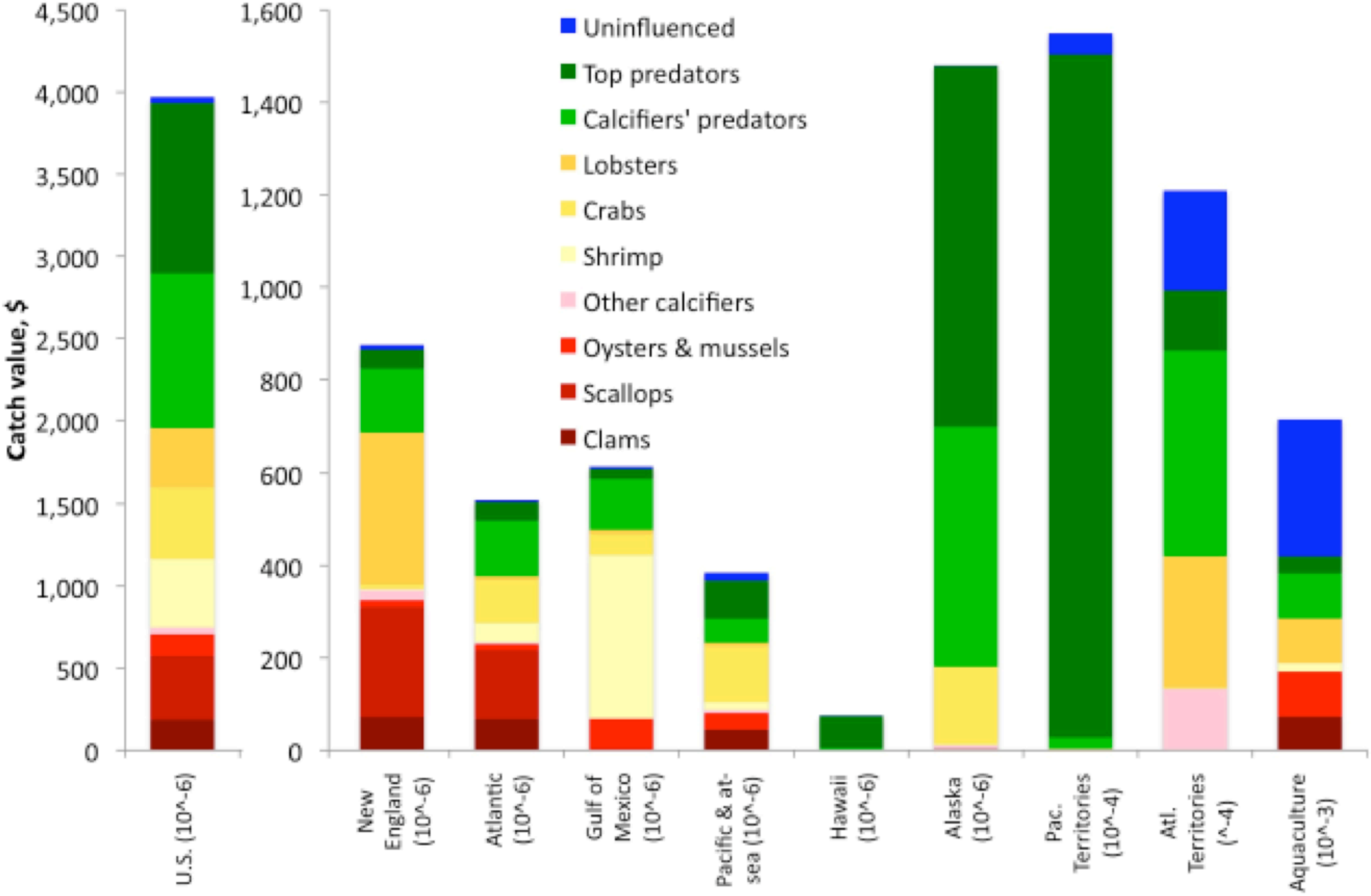
Category	Species	pH	CO2	Shell Dissol	Incr. mortality	Other
Mussel	*M. edulis*	7.1	740 ppm	Y	Y	25% decrease in calcification rate
Oyster	*C. gigas*		740 ppm			10% decrease in calcification rate
Giant Scallop	*P. magellanicus*	<8.0				Decrease in fertilization, development
Clam	*M. mercenaria*	7.0–7.2		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

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

Recreational	
Total economic impact[1]	$42,868 million
Jobs supported	349,119
Commercial	
Domestic ex-vessel revenue	$ 3,765 million
+ Harvest outside U.S.	$ 159 million
+ Aquaculture	$ 1,244 million
Primary sales	$ 5,168 million
Retail sales	$ 68,390 million
GNP contribution	$ 34,159 million

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


(a)
(b)
(c)
A1FI
A2
B1
B2
Atm. CO_2 (ppm)
Avg. Surf. pH
Avg. Surf. Ω_{Ar}
Year
Year
Year
1000
800
600
400
200
8.2
8.1
8
7.9
7.8
7.7
7.6
5
4
3
2
1
0
1950
2000
2050
2100


Catch value, $
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
1,600
1,400
1,200
1,000
800
600
400
200
0
Uninfluenced
Top predators
Calcifiers' predators
Lobsters
Crabs
Shrimp
Other calcifiers
Oysters & mussels
Scallops
Clams
U.S. (10^-6)
New England (10^-6)
Atlantic (10^-6)
Gulf of Mexico (10^-6)
Pacific & at-sea (10^-6)
Hawaii (10^-6)
Alaska (10^-6)
Pac. Territories (10^-4)
Atl. Territories (^-4)
Aquaculture (10^-3)

Supplementary material for Cooley & Doney 2009, “Anticipating ocean acidification’s economic consequences on commercial fisheries.”

NMFS-tracked species and their categories in this paper.

Not included in analysis
FINFISHES, UNC BAIT AND ANIMAL FOOD
FINFISHES, UNC FOR FOOD
FINFISHES, UNC GENERAL

Clams
CLAM, ARC, BLOOD
CLAM, ATLANTIC JACKKNIFE
CLAM, ATLANTIC SURF
CLAM, BUTTER
CLAM, MANILA
CLAM, NORTHERN QUAHOG
CLAM, OCEAN QUAHOG
CLAM, PACIFIC GEODUCK
CLAM, PACIFIC LITTLENECK
CLAM, PACIFIC RAZOR
CLAM, PACIFIC, GAPER
CLAM, QUAHOG
CLAM, SOFTSHELL
CLAMS OR BIVALVES
COCKLE, NUTTALL

Crabs
CRAB, ATLANTIC ROCK
CRAB, BLUE
CRAB, BLUE, PEELER
CRAB, BLUE, SOFT
CRAB, BLUE, SOFT AND PEELER
CRAB, DEEPSEA GOLDEN
CRAB, DUNGENESS
CRAB, FLORIDA STONE CLAWS
CRAB, GREEN
CRAB, HORSESHOE
CRAB, JONAH
CRAB, KING
CRAB, RED ROCK
CRAB, SNOW
CRAB, SOUTHERN TANNER
CRAB, SPIDER
CRABS

Lobsters
CRAYFISHES OR CRAWFISHES
LOBSTER, AMERICAN
LOBSTER, BANDED SPINY
LOBSTER, CALIFORNIA SPINY
LOBSTER, CARIBBEAN SPINY
LOBSTER, SLIPPER

Mussels and Oysters
ABALONES
MUSSEL, BLUE
MUSSEL, CALIFORNIA
OYSTER, EASTERN
OYSTER, EUROPEAN FLAT
OYSTER, OLYMPIA
OYSTER, PACIFIC

Misc. Mollusks
ECHINODERM
LIMPETS
MOLLUSKS
PERIWINKLES
SEA URCHINS
SHELLFISH
SNAILS (CONCHS)
WHELK, KNOBBED

Scallops
SCALLOP, BAY
SCALLOP, SEA
SCALLOPS

Shrimp
MANTIS SHRIMPS
SHRIMP, BLUE MUD
SHRIMP, BRINE
SHRIMP, BROWN
SHRIMP, DENDROBRANCHIATA
SHRIMP, GHOST
SHRIMP, MARINE, OTHER
SHRIMP, OCEAN
SHRIMP, PACIFIC ROCK
SHRIMP, PENAEID
SHRIMP, PINK
SHRIMP, ROCK
SHRIMP, ROYAL RED
SHRIMP, SEABOB
SHRIMP, SPOT
SHRIMP, WHITE

Calcifiers' predators
ALEWIFE
ALFONSIN
AMBERJACK
AMBERJACK, GREATER
AMBERJACK, LESSER
ANCHOVY, NORTHERN
BALLYHOO
BARRELFISH
BIGEYE
BROTULA, BEARDED
BUTTERFLYFISHES
CABEZON
COBIA
COD, ATLANTIC
DRUM, BLACK
DRUM, RED
DRUMS
EMPERORS
ESCOLAR
GLASSEYE SNAPPER
GOATFISHES
GRAYSBY
GRENADIERS
GROUPER, MARBLED
GROUPER, MISTY
GROUPER, RED
GROUPER, SNOWY
GROUPER, WARSAW
GROUPER, YELLOWEDGE
GROUPER, YELLOWFIN
GROUPER, YELLOWMOUTH
GROUPERS
GRUNT, WHITE
GRUNTS
HADDOCK
HAKE, ATLANTIC, RED/WHITE
HAKE, PACIFIC (WHITING)
HERRING, ATLANTIC
HERRING, ATLANTIC THREAD

HERRING, BLUEBACK
HERRING, PACIFIC
HERRING, SEA
HERRINGS
HIND, ROCK
HIND, SPECKLED
HOGFISH
JACK, ALMACO
JACK, HORSE-EYE
KING WHITING
LEATHERJACKETS
MACKEREL, ATLANTIC
MACKEREL, KING
MACKEREL, KING AND CERO
MENHADEN
MOJARRAS
MOONFISH, ATLANTIC
OCTOPUS
OILFISH
PERMIT
PORGY, JOLTHEAD
PORGY, KNOBBED
PORGY, RED
PORGY, WHITEBONE
POUT, OCEAN
PUFFERS
RATFISH SPOTTED
RAY,STINGRAYS
RAYS
REDFISH OR OCEAN PERCH
ROCKFISH, AURORA
ROCKFISH, BANK
ROCKFISH, BLACK
ROCKFISH, BLACK-AND-YELLOW
ROCKFISH, BLACKGILL
ROCKFISH, BLUE
ROCKFISH, BOCACCIO
ROCKFISH, BRONZESPOTTED
ROCKFISH, BROWN
ROCKFISH, CANARY
ROCKFISH, CHILIPEPPER
ROCKFISH, CHINA
ROCKFISH, COPPER
ROCKFISH, DARKBLOTCHED
ROCKFISH, FLAG
ROCKFISH, GOPHER
ROCKFISH, GRASS
ROCKFISH, GREENBLOTCHED
ROCKFISH, GREENSPOTTED
ROCKFISH, GREENSTRIPED
ROCKFISH, KELP
ROCKFISH, OLIVE
ROCKFISH, PACIFIC OCEAN PERCH
ROCKFISH, REDBANDED
ROCKFISH, REDSTRIPE
ROCKFISH, ROSY
ROCKFISH, SHARPCHIN
ROCKFISH, SHORTBELLY
ROCKFISH, SPECKLED
ROCKFISH, SPLITNOSE
ROCKFISH, STARRY
ROCKFISH, SWORDSPINE
ROCKFISH, TREEFISH
ROCKFISH, VERMILION
ROCKFISH, WIDOW
ROCKFISH, YELLOWEYE
ROCKFISH, YELLOWTAIL
ROCKFISHES
ROSEFISH, BLACKBELLY
SAND PERCH
SCAD, BIGEYE
SEA BASS, BANK
SEA BASS, GIANT
SEA BASS, ROCK
SEA RAVEN
SEAROBINS
SEATROUT, SAND
SHEEPHEAD, CALIFORNIA
SKATE, BIG
SKATES
SMELT, RAINBOW
SNAKE MACKEREL
SNAPPER, CUBERA
SNAPPER, DOG
SNAPPER, GRAY
SNAPPER, LANE
SNAPPER, MUTTON
SNAPPER, QUEEN
SNAPPER, SILK
SNAPPER, VERMILION
SNAPPERS
SOLE, DOVER
SOLE, ENGLISH
SOLE, FLATHEAD
SOLE, PETRALE
SOLE, REX
SOLE, ROCK
SOLE, SAND
SPADEFISHES
SPOT
SQUIRRELFISHES
STURGEON, GREEN
STURGEON, WHITE
SURFPERCHES
TARPON, HAWAIIAN
TAUTOG
THORNYHEAD, SHORTSPINE
THREADFINS
TILEFISH
TILEFISH, BLUELINE
TILEFISH, GOLDFACE
TILEFISH, SAND
TILEFISHES
TRIGGERFISH, GRAY
TRIPLETAIL
TROUT, RAINBOW
WOLF-EEL
WOLFFISH, ATLANTIC
ATKA MACKEREL
BASS, LONGTAIL
MACKEREL, CHUB
BASS, STRIPED
BLACK DRIFTFISH
BUTTERFISH
COD, PACIFIC
CROAKER, ATLANTIC
CROAKER, PACIFIC WHITE
CUNNER
CUSK
EEL, AMERICAN
EEL, CONGER
EEL, MORAYS
EELS
EELS, SNAKE
FLATFISH
FLOUNDER, ARROWTOOTH
FLOUNDER, PACIFIC, SANDDAB
FLOUNDER, SOUTHERN
FLOUNDER, STARRY
FLOUNDER, SUMMER
FLOUNDER, WINDOWPANE
FLOUNDER, WINTER
FLOUNDER, WITCH
FLOUNDER, YELLOWTAIL
FLOUNDER,ATLANTIC,PLAICE
FLOUNDER,PACIFIC,SANDDAB
FLOUNDERS, RIGHTEYE
GAG
HAKE, OFFSHORE SILVER
HAKE, SILVER
HAKE, WHITE
HALIBUT, ATLANTIC
HALIBUT, GREENLAND
HALIBUT, PACIFIC

HARVESTFISH
PERCH, WHITE
PERCH, YELLOW
POLLOCK
POMFRETS
POMPANO, AFRICAN
POMPANO, FLORIDA
SCULPINS
SCUP
SCUPS OR PORGIES
SEA BASS, BLACK
SEA CUCUMBER
SEATROUT, SPOTTED
SHEEPSHEAD
SNAPPER, BLACK
SNAPPER, RED
WEAKFISH
CUTLASSFISH, ATLANTIC
HAKE, RED
HIND, RED
JACK MACKEREL
PIGFISH
PINFISH

Top Predators
BARRACUDA, PACIFIC
BARRACUDAS
BILLFISHES
BLUEFISH
BONITO, ATLANTIC
BONITO, PACIFIC
DEALFISH
DOLPHINFISH
DORY, AMERICAN JOHN
GARS
GOOSEFISH
GREENLING, KELP
GROUPER, BLACK
HALIBUT, CALIFORNIA
JACK, BAR
JACK, BLACK
JACK, CREVALLE
JACKS
JOBFISH, GREEN (UKU)
LADYFISH
LINGCOD
LOOKDOWN
MACKEREL, FRIGATE
MACKEREL, SPANISH
MARGATE
MARLIN, BLACK
MARLIN, BLUE
MARLIN, STRIPED
MUMMICHOG
OPAH
POLLOCK, WALLEYE
RUDDERFISH, BANDED
RUNNER, BLUE
RUNNER, RAINBOW
SABLEFISH
SAILFISH
SALMON, CHINOOK
SALMON, CHUM
SALMON, COHO
SALMON, PINK
SALMON, SOCKEYE
SCAMP
SHARK, ATLANTIC SHARPNOSE
SHARK, BIGEYE THRESHER
SHARK, BLACKNOSE
SHARK, BLACKTIP
SHARK, BLUE
SHARK, BONNETHEAD
SHARK, BULL
SHARK, DOGFISH
SHARK, FINETOOTH
SHARK, HAMMERHEAD
SHARK, LEMON
SHARK, LEOPARD
SHARK, LONGFIN MAKO
SHARK, MAKOS
SHARK, PACIFIC ANGEL
SHARK, PORBEAGLE
SHARK, SAND TIGER
SHARK, SANDBAR
SHARK, SHORTFIN MAKO
SHARK, SMOOTH DOGFISH
SHARK, SOUPFIN
SHARK, SPINNER
SHARK, SPINY DOGFISH
SHARK, THRESHER
SHARK, TIGER
SHARKS
SNAPPER, BLACKFIN
SNAPPER, YELLOWTAIL
SOLE, YELLOWFIN
SPEARFISHES
SQUID, CALIFORNIA MARKET
SQUID, JUMBO
SQUID, LONGFIN
SQUID, NORTHERN SHORTFIN
SQUID, ROBUST CLUBHOOK
SQUIDS
SUCKERS
SWORDFISH
THRESHER SHARKS
TOADFISHES
TUNA, ALBACORE
TUNA, BIGEYE
TUNA, BLACKFIN
TUNA, BLUEFIN
TUNA, BLUEFIN PACIFIC
TUNA, KAWAKAWA
TUNA, LITTLE TUNNY
TUNA, SKIPJACK
TUNA, YELLOWFIN
TUNAS
TURTLE, SOFT-SHELL
WAHOO
YELLOWTAIL JACK

Uninfluenced/unknown
BLOODWORMS
HAGFISHES
LEATHER-BACK
MULLET, STRIPED (LIZA)
MULLET, WHITE
MULLETS
OCEAN SUNFISH
PARROTFISHES
PINFISH, SPOTTAIL
PRICKLEBACK, MONKEYFACE
SANDWORMS
SARDINE, PACIFIC
SARDINE, SPANISH
SCAD, MACKEREL
SCADS
SCORPIONFISH, SPINYCHEEK
SCORPIONFISHES
SEA CATFISHES
SEA CHUBS
SEABASS, WHITE
SEAWEED, IRISH MOSS
SEAWEED, KELP
SEAWEED, ROCKWEED
SEAWEEDS
SHAD, AMERICAN
SHAD, GIZZARD
SHAD, HICKORY
SKIPPERS
SMELT, EULACHON
SMELTS
SOLE, CURLFIN
SPONGE, GRASS
SPONGE, SHEEPSWOOL
SPONGE, YELLOW
SPONGES
SUNFISHES
SURGEONFISHES

Freshwater species -- not included in analysis

BASS, ROCK
BASS, WHITE
BOWFIN
BUFFALOFISHES
BURBOT
CARP, COMMON
CARP, GRASS
CARPS AND MINNOWS
CATFISH, BLUE
CATFISH, CHANNEL
CATFISH, FLATHEAD
CATFISHES & BULLHEADS
CHUBS
CRAPPIE
DRUM, FRESHWATER
GOLDFISH
HERRING, LAKE OR CISCO
QUILLBACK
TILAPIAS
TROUT, LAKE
TURTLE, SLIDERS
TURTLE, SNAPPING
TURTLE, TERRAPIN
TURTLES
WALLEYE
WHITEFISH, LAKE
WHITEFISH, ROUND