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Welfare Estimates of Avoided Ocean Acidification in the U.S. Mollusk Market

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Ocean acidification has the potential to adversely affect a number of valuable marine ecosystem services by making it more difficult, and eventually impossible, for many marine organisms to form shells and skeletons. Reef-forming corals, commercially valuable shellfish, and primary producers that form the base of the marine food web are among the affected organisms. Despite the range and magnitude of likely impacts, very few economic analyses of ocean acidification's consequences have been conducted. This paper adds to the emerging body of literature by taking a distance function approach to estimating the benefits of avoided ocean acidification in the U.S. mollusk market. A nonlinear inverse almost ideal demand system estimates the utility parameters needed to calculate the exact consumer welfare measures compensating and equivalent surplus for two hypothetical policies that would reduce global greenhouse gas emissions relative to a business-as-usual scenario.

Key words: compensating surplus, equivalent surplus, inverse demand system, ocean acidification

Introduction

Ocean acidification, called "the other CO_2 problem" by Doney et al. (2009), has the potential to adversely affect a number of valuable marine ecosystem services. As the atmospheric concentration of carbon dioxide (CO_2) increases, the ocean absorbs more of the gas, causing changes in seawater chemistry. These changes make it more difficult for some marine organisms to form shells and skeletons. Among the organisms most directly affected are commercially harvested mollusks like clams and oysters. This paper models the potential impacts on the U.S. mollusk fishery and compares consumer welfare benefits across future CO_2 emission reduction scenarios. While ocean acidification is distinct from global warming, the fact that they have a common cause suggests they should be considered together, particularly when examining policies that would affect the future trajectory of CO_2 emissions.

The ocean is the Earth's largest sink of atmospheric CO_2 and has absorbed about one-third of anthropogenic CO_2 emissions over the past 200 years (Sabine et al., 2004). When absorbed into the ocean, CO_2 forms carbonic acid, lowering the seawater pH and the aragonite saturation level (Ω_A). As Ω_A falls it becomes more difficult, and eventually impossible, for many marine organisms to form shells and skeletons. Mollusks and reef-building corals appear to be particularly vulnerable while crustaceans, like lobsters and crabs, are not adversely affected (Ries, Cohen, and McCorkle, 2009; Kroeker et al., 2010).

Regulations and agreements that reduce carbon dioxide emissions, such as fuel economy standards in the United States or the European Union Emissions Trading System, mitigate the impacts of climate change and ocean acidification. To develop efficient mitigation policy, decision makers should weigh the expected social costs of these policies against the economic damages that

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are likely to be avoided as a result. There is a large body of literature estimating the economic impacts of climate change caused by CO_2 and other greenhouse gasses, but the impacts of ocean acidification are conspicuously absent from that literature. Only recently have there been efforts to estimate ocean acidification's potential economic impacts. So far they have examined the mollusk fishery (Cooley and Doney, 2009; Narita, Rehdanz, and Tol, 2012) and ecosystem services provided by coral reefs (Brander et al., 2012).

This study differs from others examining the economic impact of ocean acidification in several potentially useful ways. First, it estimates the exact consumer welfare measures compensating and equivalent surplus and it does so in quantity space, which is the preferred approach when examining markets for seafood and other highly perishable commodities (Barten and Bettendorf, 1989). Second, impacts to mollusk species are modeled separately while the utility parameters are estimated simultaneously in a nonlinear inverse demand system. Other economic analyses of ocean acidification's impact on commercial fisheries have applied a single response to all species, ignoring observed variation among different types of shellfish. This study accounts for the responses that different mollusk types have to falling Ω_A and the substitution patterns consumers exhibit among them, allowing for the possibility that consumers will react to changes in relative prices by substituting toward mollusk types that are less affected by ocean acidification. Failing to account for differences in mollusk responses and substitution patterns in their consumption is likely to bias welfare estimates. Finally, this study estimates the discounted flow of benefits from two hypothetical emission reduction policies relative to a forecast of business-as-usual emissions. Previous economic analyses of ocean acidification's economic impacts have compared conditions expected at a single point in the future to current conditions, which is a useful illustration but less policy relevant.

Some types of mollusks are more sensitive to changing conditions than others. In fact, some types exhibit no significant response at all to the conditions we might expect by the end of the century. But for the types that exhibit a reaction to falling Ω_A, the central estimates from this analysis show harvests falling by 41% to 54% by the end of the century under the business-as-usual scenario compared with a decrease of 7% to 20% under the most optimistic policy scenario. Data from the U.S. mollusk fishery is used to estimate consumer welfare gains from the lower emissions trajectories relative to baseline. The resulting consumer welfare impacts are particularly sensitive to the choice of a discount rate because the annual damages are increasing over a long time horizon. Using a discount rate of 3%, the net present value of benefits to U.S. consumers from the most optimistic policy path is nearly $1 billion with undiscounted annual benefits reaching $440 million at the end of the century.

Consumer Welfare Estimation in Quantity Space

Barten and Bettendorf (1989) made the case that demands for perishable goods like produce, meat, and seafood should be examined using inverse demand equations in which quantity is treated as exogenous and price adjusts to clear the market. Since then, inverse demand estimation has dominated this area of research (e.g., Eales and Unnevehr, 1994; Holt and Bishop, 2002; Park, Thurman, and Easley Jr., 2004; Wong and McLaren, 2005; Thong, 2012). Kim (1997) showed how the distance function, which is dual to the expenditure function, can be used to estimate consumer welfare effects from changes in supply. Using Shephard's lemma one can derive compensated inverse demand equations from the distance function allowing empirical estimation of utility theoretic welfare measures in quantity space.

The distance function can be considered a normalized money metric utility function (Kim, 1997). Given the quantity vector x and a direct utility function $u = F(x)$, the distance function $D(u,x)$ is defined as

$$D(u,x) = \max_t \{t > 0 : F(x/t) > 0\}, \tag{1}$$

which gives the maximum amount by which the quantity vector can be divided and still reach the indifference surface.

Exact measures of consumer welfare can be calculated from the distance function by finding the difference between $D(u,x)$ evaluated at different quantity vectors, x^0 and x^1, given a reference utility level u^0 or u^1. Specifically, the normalized compensating and equivalent surplus from a change in supply are

(2) $$\overline{CS} = D(u^0,x^1) - D(u^0,x^0) \text{ and}$$

(3) $$\overline{ES} = D(u^1,x^1) - D(u^1,x^0).$$

The normalized measures $\overline{CS}$ and $\overline{ES}$ must be adjusted by total expenditures on the commodity group (or by income for a complete demand system) to arrive at monetary measures of welfare impacts CS and ES. If expenditures are expected to change in the counterfactual case, then the non-normalized welfare measures are expressed as

(4) $$CS = Y^0.\left[D(u^0,x^1) - D(u^0,x^0)\right] - (Y^1 - Y^0);$$

(5) $$ES = Y^1.\left[D(u^1,x^1) - D(u^1,x^0)\right] - (Y^1 - Y^0);$$

where Y^0 and Y^1 are expenditures before and after the change in quantities (Kim, 1997).

Utility is not observable, so the distance function cannot be estimated directly. To estimate the parameters of the distance function it is necessary to choose a functional form and derive the resulting system of compensated inverse demands. These demands can be estimated empirically and used to recover the parameters needed for welfare analysis. A number of functional forms for the distance function have been used in the literature. A popular choice is the Inverse Almost Ideal (IAI) specification (Eales and Unnevehr, 1994; Moschini and Vissa, 1992):

(6) $$\ln[D(u,x)] = a(x) - ub(x),$$

where $a(x) = \alpha_0 + \sum_i \alpha_i \ln(x_i) + \frac{1}{2}\sum_i \sum_j \gamma_{ij} \ln(x_i)\ln(x_j)$; $b(x) = \beta_0 \Pi_i x_i^{\beta_i}$; $\boldsymbol{\alpha}$, $\boldsymbol{\gamma}$, and $\boldsymbol{\beta}$ are estimated utility parameters and x_i are elements of the quantity vector $\boldsymbol{x}$. Because $D(u,\boldsymbol{x})$ is homogeneous of degree one in $\boldsymbol{x}$, the following aggregation restrictions apply: $\sum_i \alpha_i = 1$, $\sum_j \gamma_{ij} = \sum_i \gamma_{ij} = 0$, and $\sum_i \beta_i = 0$. Utility maximization also requires symmetry of $\boldsymbol{\gamma}$ so that $\gamma_{ij} = \gamma_{ji}$.

According to Shephard's theorem, the first derivatives of the distance function with respect to quantities yield normalized compensated inverse demands:

(7) $$\hat{P} = \frac{\partial D(u,x)}{\partial x} = a(u,x),$$

where $\hat{P} = P/Y$, P is a vector of prices, and Y is total expenditures on $\boldsymbol{x}$. Applying Shephard's theorem to the IAI form of the distance function—recognizing that $\frac{\partial \ln D}{\partial \ln x_i} = \frac{\partial D}{\partial x_i}\frac{x_i}{D}$ and that identification of the direct utility function requires that $D = 1$ (Deaton, 1979)—yields the compensated inverse demand system in expenditure share form

(8) $$w_i = \frac{p_i x_i}{Y} = \alpha_i + \sum_j \gamma_{ij} \ln(x_j) - u\beta_i b(x),$$

where w_i is the expenditure share of x_i and p_i is an element of P. But u is unobservable, so using $D = 1$, invert the distance function (6) for $u = \frac{a(x)}{b(x)}$ and plug into the inverse demands, yielding the nonlinear system of expenditure share equations

(9) $$w_i = \alpha_i + \sum_j \gamma_{ij} \ln(x_j) - \beta_i \ln Q,$$

where the quantity index $\ln Q \equiv a(x)$.

In an inverse demand system the price and scale flexibilities are analogous to the price and expenditure elasticities of a direct demand system and can be interpreted in similar ways. A price flexibility represents the change in the market clearing price of a particular good given a change in the supply of that good (in the case of own-price flexibilities) or another good (in the case of cross-price flexibilities). Similar to their direct demand counterparts, own-price flexibilities will be negative for normal goods. Scale flexibilities are analogous to the expenditure elasticities of direct demand estimation and represent the change in price if all goods in the consumption bundle were scaled by the same proportion. A proportional increase in the commodity vector will cause prices to fall for goods with a downward sloping demand curve, implying negative scale elasticities in those cases. Scale flexibilities less than -1 indicate that necessities and luxury goods have scale flexibilities between -1 and 0. While the estimated flexibilities will not be used in the welfare analysis directly, prior expectations on their signs and magnitudes provide a theoretical check on the estimated demand parameters.

Eales and Unnevehr (1994) derive expressions for the price and scale flexibilities of the IAI demand system and show that they are fairly straightforward translations of their direct demand counterparts. For the IAI demand model, the uncompensated own- and cross-price flexibilities for goods i and j, $\partial \ln(p_i)/\partial \ln(x_j)$, are given by

$$e_{ij} = \frac{g_{ij} + b_i(w_j - b_j \ln Q)}{w_i} - d_{ij}, \tag{10}$$

where $d_{ij} = 1$ if $i = j$ and $d_{ij} = 0$ otherwise. If θ is a constant scaling of the quantity vector, scale flexibilities are defined as $\partial \ln(p_i(\theta q))/\partial \ln(\theta)$ and are given by

$$S_i = \frac{b_i}{w_i} - 1. \tag{11}$$

Compensated own- and cross price flexibilities are given by

$$\tilde{e}_{ij} = e_{ij} - w_j S_i. \tag{12}$$

Forecasting Ocean Acidification Impacts on U.S. Mollusk Supply

To compare consumer welfare across different CO_2 emission scenarios, the entire ocean acidification "impact pathway" is modeled and simulated (figure 1). The simulation begins with future CO_2 and other greenhouse gas (GHG) emissions as inputs into models of sea surface temperature (SST) and seawater chemistry. These models produce the forecasts for Ω_A, which are used with a set of reaction functions to find the expected change in mollusk growth and survival.

The empirical link between physiological effects and shellfish harvest is the weakest in the chain of ocean acidification impacts on the mollusk market. All of the studies of ocean acidification's impacts rely on changes in shell growth rates or changes in weight as a proxy for market impacts (Cooley and Doney, 2009; Narita, Rehdanz, and Tol, 2012; Brander et al., 2012). This requires at least two assumptions. First, it requires assuming that the broader population impacts will be proportional to the effects that ocean acidification has on individual organisms. Mesocosm experiments that observe multiple interacting species over a number of generations would provide much needed insight into how large populations would be affected (Hilmi et al., 2013). Secondly, it implicitly assumes that producers will not adapt to the changing conditions to lessen the impact on market supply. Either of these assumptions could result in biased estimates of the economic impacts. While the direction of the bias resulting from the assumption regarding population impacts is not clear, the assumption that supply will be affected proportionally almost certainly results in an upward bias for welfare estimates. Acknowledging these limitations, but lacking a better alternative at this

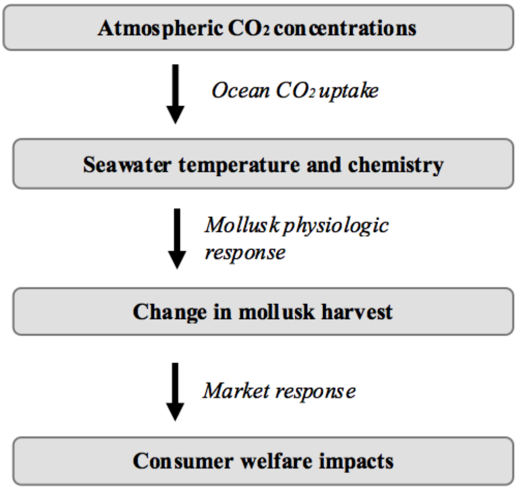

Figure 1. Ocean Acidification Impact Pathway

time, this study follows precedent and sets the rate of harvest loss over time equal to the change in growth rate for each species.

Projections of CO_2 and other GHG emissions and the resulting radiative forcing are taken from the Representative Concentration Pathways (RCP, van Vuuren et al., 2011), which were generated for the IPCC Fifth Assessment Report. The concentration pathways are distinguished by the resulting radiative forcing at the end of this century. Radiative forcing is the difference between the amount of energy the Earth receives from the sun and the amount reflected back into space expressed in watts per square meter (w/m^2). Larger positive numbers indicate more energy is being trapped in the Earth's atmosphere. The model developed in this paper will operate on three of the RCP scenarios treating the high-emissions pathway (8.5 w/m^2 radiative forcing in 2100) as the business-as-usual scenario and examining the medium-high pathway (6 w/m^2 radiative forcing in 2100) and the medium-low pathway (4.5 w/m^2 radiative forcing in 2100) as policy scenarios that reduce GHG emissions relative to the baseline.

The relationship between atmospheric CO_2 concentrations and ocean acidification is described, in part, by Henry's Law, which states that "at a constant temperature, the amount of a given gas that dissolves in a given type and volume of liquid is directly proportional to the partial pressure (pCO_2) of that gas in equilibrium with that liquid" (UC Davis Department of Chemistry, 2011). However, when temperature is not constant, the relationship changes and, in fact, as seawater gets warmer as a result of climate change it will absorb less CO_2 from the atmosphere. So in addition to the pathways for atmospheric CO_2 concentration, the SST is also required for reliable forecasts of Ω_A. The upwelling diffusion energy balance model of Baker and Roe (2009) will be used to forecast SST. The Baker and Roe model is an aspatial representation of the energy exchange between the atmosphere and a well-mixed surface layer of the ocean which loses heat to the deep ocean below.

With projections of CO_2 concentration and SST, the ocean carbon model CO2SYS (Lewis, Wallace, and Allison, 1998; van Heuven et al., 2009) is used to forecast changes in seawater chemistry. The CO2SYS model uses two of the four measureable parameters of the CO_2 system (total alkalinity, total inorganic CO_2, pH, and pCO_2) to calculate the two unknown parameters and Ω_A at a given SST. Current measures of total inorganic carbon are used to initialize the model after which they are generated within the simulation.

Most studies of the impact of ocean acidification on marine organisms observe species with little or no direct market value under CO_2 concentrations that far exceed that which is feasible in the next century (Hilmi et al., 2013). Ries, Cohen, and McCorkle (2009) is one of the few published studies

Table 1. GDP and Expenditure Forecasts

Year	U.S. GDP Forecast (trillions of 2010 USD)	Annual U.S. Mollusk Expenditures (millions of 2010 USD)
2010	14.62	431.0
2020	18.68	427.0
2030	22.75	455.6
2040	26.94	461.1
2050	31.42	469.1
2060	35.57	475.7
2070	40.22	482.2
2080	45.06	488.4
2090	50.15	494.2
2100	55.15	499.9

that examine economically important species under CO_2 concentrations we are likely to see this century. They observe the effect of increased CO_2 on calcification rates of a number of species and perform regression analysis using the observed Ω_A as an independent variable.[1] The result is a set of reaction functions that can be applied to the range of CO_2 concentrations in the RCP pathways to forecast calcification rates under expected Ω_A levels. The resulting time path for changes in growth rates will be applied to average harvests over the last five years of market data to generate a supply vector for the years 2011 through 2100.

Data

Estimating the coefficients of the inverse demand system requires data on U.S. domestic consumption and prices. Consumption was calculated using monthly landings data from 1990 through 2010 and subtracting net exports of live or fresh mollusks (National Marine Fisheries Service). Forecasting welfare impacts through the end of the century requires predictions of expenditures on the commodity group Y. To project a time path for expenditures on mollusks, the 2009 Stanford Energy Modeling Forum (EMF) projection of U.S. GDP through the end of the century is used to find a growth rate for personal income. The EMF economic scenarios are widely used in the climate change literature, including the International Panel on Climate Change (IPCC) Fifth Assessment Report. The EMF economic scenarios are also one of the few sources that provide a U.S. GDP projection through the end of the century (see Clarke et al., 2009, for an overview of the model and results). The GDP projection is combined with an income elasticity for shellfish expenditures to find the expenditure growth rate. Cheng and Capps (1988) analyze the demand for finfish and shellfish in the United States and provide an estimate of the income elasticity for shellfish expenditures of 0.11. Decadal forecasts of GDP and the resulting estimates of mollusk expenditures are shown in table 1.

A market value-weighted ten-year average of SST for the coastal regions of the United States where mollusks are harvested and cultured (NOAA National Oceanographic Data Center) was used to generate a single representative starting value: $\overline{SST} : \frac{1}{10}\sum_t \sum_r \frac{v_{rt}}{V_t} SST_{rt}$, where the subscripts r and t denote the region and year, v is the value of shellfish harvest from a given region, and V is the total value of shellfish harvest from all regions. The forecasted time paths for SST under the three RCP scenarios are shown on the left-hand side of figure 2. The right-hand side of figure 2 shows the

[1] Ries et al. find that some crustaceans, including lobster and shrimp, show an increase in adult calcification rates under higher CO_2 levels. A meta-analysis performed by Kroeker et al. (2010) shows that this is a common result but also finds a non-significant negative impact on juvenile survival rates. Another meta-analysis by Wittmann and Pörtner (2013) examines differences among shellfish taxa in response to ocean acidification and concludes, “all considered groups are impacted negatively, albeit differentially, even by moderate ocean acidification” (page 999). Because the impacts on crustaceans are less definitive than those on mollusks the scope of this analysis is restricted to mollusks.

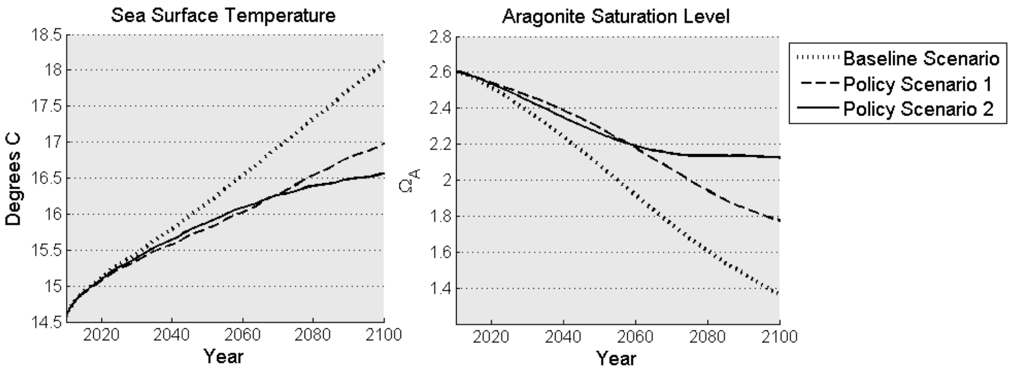

Figure 2. Forecasts of Sea Surface Temperature and Aragonite Saturation Level

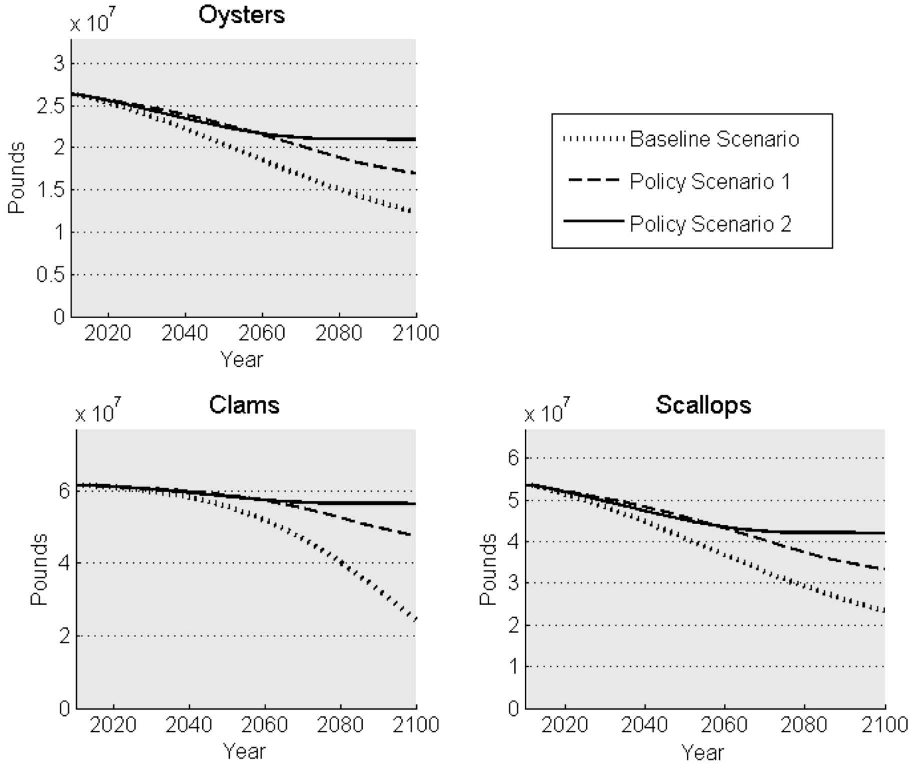

Figure 3. Forecast of Annual Mollusk Harvest

results of the CO2SYS model using the CO_2 concentrations from the three RCP scenarios and their associated SST forecasts.

Ries, Cohen, and McCorkle (2009) test a number of functional forms for the reaction function of each observed species and report the coefficient estimates from the regression that resulted in the lowest mean squared error (table 2). Mussels did not exhibit a statistically significant reaction to increasing CO_2 concentrations (and falling Ω_A), so the supply of mussels will be held fixed at the

Table 2. Mollusk Reaction Functions Reported in Ries, Cohen, and McCorkle (2009)

Species	Best Fit Regression (Sixty-day percentage change in weight regressed on Ω_A)	R^2	Root Mean Squared Error
Eastern Oyster	$\%\Delta wt = 0.84\Omega_A - 0.23$	0.76	0.36
Bay Scallop	$\%\Delta wt = 2.37\Omega_A - 0.97$	0.34	2.61
Hard Clam	$\%\Delta wt = -10.3e^{2.1\Omega_A} + 0.94$	0.83	0.44

most recent five-year average in the welfare calculations that follow.[2] Using the Ries, Cohen, and McCorkle (2009) reaction functions and the forecasted Ω_A levels, the expected changes in mollusk growth rates are applied to the most recent five-year average of annual harvest to forecast supply through 2100. Figure 3 shows the forecasted harvest for oysters, scallops and clams.

Results

The parameters of the IAI demand system (9) were estimated via nonlinear seemingly unrelated regression. The aggregation conditions were imposed by estimating the inverse demand equations for oysters, scallops, and clams and solving for the parameters of the mussel equation. The symmetry condition was imposed by only estimating the upper triangle of the $\boldsymbol{\gamma}$ matrix. Perhaps more meaningful for interpretation than the parameter estimates themselves are the resulting price and scale flexibilities, which are functions of all estimated parameters. Using the full covariance matrix of the demand system parameters, 1,000 draws of the parameter vector are used in a Krinsky and Robb (1986) simulation to provide a simulated distribution of price and scale flexibilities (table 3) evaluated at the sample mean. All of the means and all but one of the inner 90th percentiles for scale and price flexibilities lie below zero, which is what one would expect for normal goods with downward sloping demand curves. Mussels are the one exception, with an upper bound of 0.207 on their own-price elasticity. Overall, prices tend to be fairly inelastic to changes in quantity, which is consistent with other analyses of mollusk markets (e.g., Eales, Durham, and Wessells, 1997; Thong, 2012). The flexibilities provide an intuitive check on the specification of the inverse demand system. Given that the flexibilities are well-behaved we can be more confident in using the parameter estimates for welfare analysis.

To generate a probabilistic distribution for the consumer welfare benefits, another numerical simulation provides 1,000 draws of growth rate changes for each mollusk type. Plugging the forecasted time path of Ω_A into the regression equations of table 2 provides a time-vector of mean growth rates for each species (figure 3). The root mean squared errors reported by Ries et al. are then used to draw normally distributed disturbances around the forecasted means to generate a distribution of growth rates. The change in those growth rates is then used to infer supply changes over time for each type of mollusk (table 4). Apart from mussels—which showed no response to increased CO_2—the mean forecasted harvest losses through the end of the century under the business-as-usual scenario range from 41% to 54% depending on the species. Considering the null response for mussels, these harvest losses are on the same order as those used in two previous studies on ocean acidification's impacts on mollusk markets. Cooley and Doney (2009) generated estimates using 10% and 25% harvest losses for all mollusks while Narita, Rehdanz, and Tol (2012) use central estimates of 43% and 35% and a confidence interval of 0–62%.

Draws of the forecasted baseline and policy supply vectors are combined with the draws of the utility parameters to evaluate expressions (4) and (5) for the annual compensating and equivalent surplus for each scenario and discounted at constant rates of 3%, 5%, and 7%. The distributions for compensating surpluses are reported in table 5 and equivalent surpluses are shown in table 6. There is very little difference in welfare impacts between the two scenarios despite the rather large difference in CO_2 concentrations at the end of the century. This is because the path of GHG concentrations is

[2] O'Donnell, George, and Carrington (2013) found that the material mussels create to attach to substrate is weakened by ocean acidification, which could reduce survival rates. This effect is not accounted for here, however.

Table 3. Simulated Distributions for Inverse Demand Flexibilities

	Mean	Lower 5th Percentile	Upper 95th Percentile
Uncompensated Price			
Oyster	−0.474	−0.533	−0.412
Scallop	−0.588	−0.614	−0.566
Clam	−0.395	−0.455	−0.337
Mussel	−0.166	−0.431	−0.100
Compensated Price			
Oyster	−0.165	−0.224	−0.105
Scallop	−0.035	−0.053	−0.018
Clam	−0.387	−0.453	−0.325
Mussel	−0.037	−0.309	0.207
Scale			
Oyster	−1.443	−1.509	−1.376
Scallop	−0.853	−0.874	−0.834
Clam	−0.085	−0.175	−0.010
Mussel	−3.015	−3.304	−2.738

Table 4. Forecasted Change in Harvest under Different Emission Scenarios through the Year 2100

	Mean	Lower 5th Percentile	Upper 95th Percentile
Oyster			
Business as usual	-53%	-90%	-30%
Policy 1	-35%	-60%	-20%
Policy 2	-20%	-35%	-12%
Scallop			
Business as usual	-41%	-85%	-20%
Policy 1	-27%	-57%	-13%
Policy 2	-16%	-33%	-8%
Clam			
Business as usual	-54%	-89%	-29%
Policy 1	-20%	-33%	-11%
Policy 2	-7%	-12%	-4%

very similar in the two scenarios for the first half of the century. Only after 2060 do the paths of Ω_A and harvests diverge significantly between the two policy scenarios (see figures 2 and 3), and by that time discounting lessens the effect on net present value. In fact, when a rate of 7% is used to discount future benefits, policy 1 has larger benefits than policy 2 because CO_2 concentrations are greater during the first half of the century under the medium-low scenario than they are under the medium-high scenario.

To present the model results in a way that provides a more direct comparison with other estimates of damages from ocean acidification and climate change an additional welfare simulation is performed holding the counterfactual supply constant at current levels and finding the total welfare impacts of ocean acidification in the U.S. mollusk market. By the end of the century the estimated annual consumer welfare impacts are about $440 million. According to the Intergovernmental Panel

Table 5. Net Present Value of Compensating Surplus in U.S. Mollusk Market from Avoided Ocean Acidification (Millions of 2010 USD)

	Discount Rate	Mean Compensating Surplus	Lower 5th Percentile	Upper 95th Percentile
Policy 1	3%	980.6	456.2	2,047.9
	5%	373.5	190.2	745.7
	7%	172.0	91.8	326.7
Policy 2	3%	1,167.1	518.2	2,540.2
	5%	390.0	189.4	810.3
	7%	159.3	82.3	313.0

Table 6. Net Present Value of Equivalent Surplus in U.S. Mollusk Market from Avoided Ocean Acidification (Millions of 2010 USD)

	Discount Rate	Mean Equivalent Surplus	Lower 5th Percentile	Upper 95th Percentile
Policy 1	3%	822.4	434.8	1,526.5
	5%	328.5	182.7	566.9
	7%	157.1	89.0	281.2
Policy 2	3%	888.0	482.2	1,614.3
	5%	339.7	188.4	576.8
	7%	139.1	78.5	249.1

Table 7. Change in Expenditure Shares and Mollusk Prices through 2100

	Change in Expenditure Shares			Change in Prices		
	Baseline	Policy 1	Policy 2	Baseline	Policy 1	Policy 2
Oysters	−0.08	−0.05	−0.02	42%	36%	27%
Scallops	0.10	0.04	0.02	125%	72%	43%
Clams	−0.01	0.01	0.00	246%	113%	58%
Mussels	−0.01	−0.01	0.00	8%	10%	13%

on Climate Change (IPCC) 1996 report the annual damages predicted by this model are on the same order as those expected from the increased frequency and severity of hurricanes of $200–$800 million per year.

In addition to the welfare impacts, the harvest forecasts and coefficients of the inverse demand system provide the means to forecast prices for each of the shellfish types under various emissions scenarios. Table 7 shows how the model predicts expenditure shares and prices to change from current levels under each scenario through the end of the century. There are two effects driving the changes in table 7. Increases in real income increase the demand for normal goods while ocean acidification impacts are simultaneously reducing the supply of three out of the four mollusk types. As one might expect, the prices of the three types that are affected by ocean acidification are positively correlated with CO_2 emissions. More severe ocean acidification impacts result in larger reductions in supply and drive the market clearing price of those shellfish higher. As for mussels, the increase in real income results in price increases over the forecast horizon but higher CO_2 scenarios result in lower prices. This shows that the scale effect (the quantity space analogue of the income effect) from decreased supply of the affected mollusk types dominates the substitution effect resulting in smaller price increases for mussels under the more severe ocean acidification scenarios.

The emissions scenarios and resulting changes in supply occur over a fairly long time horizon—longer than the time series used to estimate the parameters of the inverse demand system. In the long run, demand tends to be more elastic as consumers realize that the quantity and price changes they are observing are permanent and reallocate their expenditures accordingly. All else equal, a more elastic demand over the long run will mean smaller welfare impacts in the latter part of the forecast horizon. Discounting future welfare impacts mitigates this discrepancy, but the results in tables 5 and 6 should nonetheless be interpreted with some caution, as the model does not capture potential long-run changes in demand.

Discussion and Conclusion

Despite the potential for catastrophic impacts across a number of sectors, there are very few studies quantifying the economic impacts of ocean acidification. This is due in large part to a shortfall in the literature covering the physical impacts; economists cannot quantify the economic impacts of ocean acidification if the physical impacts are unknown. But economists should not be let off the hook entirely. Even for the relatively well understood physical impacts—those on shellfish and coral reefs—there are very few rigorous economic analyses. This paper is the first utility-theoretic welfare analysis of ocean acidification impacts and the first to model responses of different species separately.

Ocean acidification has only recently entered the discussion surrounding carbon emission reductions. It remains to be seen whether the economic impacts of ocean acidication are large enough to influence that discussion. This paper provides a partial answer to that question by estimating the incremental economic benefit of two hypothetical emissions reductions policies. Model results show that the damages in the U.S. mollusk fishery are on the same order as those estimated for increased hurricane damages in the U.S. from climate change at the end of this century. Adding estimates from coral reef damages and finfish impacts would certainly push that estimate higher. While the physical impacts to coral reefs are well documented and the resulting economic impacts have been studied, the impacts to finfisheries would be much more speculative at this time. Nor does the impact pathway modeled here necessarily end with mollusks. In marine ecosystems interaction among species will likely lead to further impacts as a result of those described in this paper. Nonetheless, there is now evidence that ocean acidification impacts can and should be included in quantitative analyses of greenhouse gas emissions reductions rather than treated as another unknown and assigned a default value of zero in benefit-cost comparisons.

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References

Baker, M. B., and G. H. Roe. "The Shape of Things to Come: Why Is Climate Change So Predictable?" *Journal of Climate* 22(2009):4574–4589. doi: 10.1175/2009JCLI2647.1.

Barten, A. P., and L. J. Bettendorf. "Price Formation of Fish: An Application of an Inverse Demand System." *European Economic Review* 33(1989):1509–1525. doi: 10.1016/0014-2921(89)90075-5.

Brander, L. M., K. Rehdanz, R. S. J. Tol, and P. J. H. van Beukering. "The Economic Impact of Ocean Acidification on Coral Reefs." *Climate Change Economics* 3(2012). doi: 10.1142/S2010007812500029.

Cheng, H., and O. Capps. "Demand Analysis of Fresh and Frozen Finfish and Shellfish in the United States." *American Journal of Agricultural Economics* 70(1988):533–542. doi: 10.2307/1241491.

Clarke, L., J. Edmonds, V. Krey, R. Richels, S. Rose, and M. Tavoni. "International Climate Policy Architectures: Overview of the EMF 22 International Scenarios." *Energy Economics* 31(2009):S64–S81. doi: 10.1016/j.eneco.2009.10.013.

Cooley, S. R., and S. C. Doney. "Anticipating Ocean Acidification's Economic Consequences for Commercial Fisheries." *Environmental Research Letters* 4(2009):024,007. doi: 10.1088/1748-9326/4/2/024007.

Deaton, A. "The Distance Function in Consumer Behaviour with Applications to Index Numbers and Optimal Taxation." *Review of Economic Studies* 46(1979):391–405. doi: 10.2307/2297009.

Doney, S. C., V. J. Fabry, R. A. Feely, and J. A. Kleypas. "Ocean Acidification: The Other CO_2 Problem." *Annual Review of Marine Science* 1(2009):169–192. doi: 10.1146/annurev.marine.010908.163834.

Eales, J., C. Durham, and C. R. Wessells. "Generalized Models of Japanese Demand for Fish." *American Journal of Agricultural Economics* 79(1997):1153–1163. doi: 10.2307/1244272.

Eales, J. S., and L. J. Unnevehr. "The Inverse Almost Ideal Demand System." *European Economic Review* 38(1994):101–115.

Hilmi, N., D. Allemand, S. Dupont, A. Safa, G. Haraldsson, P. Nunes, C. Moore, C. Hattam, S. Reynaud, J. M. Hall-Spencer, M. Fine, C. Turley, R. Jeffree, J. Orr, P. L. Munday, and S. R. Cooley. "Towards Improved Socio-Economic Assessments of Ocean Acidification's Impacts." *Marine Biology* 160(2013):1773–1787. doi: 10.1007/s00227-012-2031-5.

Holt, M. T., and R. C. Bishop. "A Semiflexible Normalized Quadratic Inverse Demand System: An Application to the Price Formation of Fish." *Empirical Economics* 27(2002):23–47. doi: 10.1007/s181-002-8357-6.

Kim, H. Y. "Inverse Demand Systems and Welfare Measurement in Quantity Space." *Southern Economic Journal* 63(1997):663–679.

Krinsky, I., and A. L. Robb. "On Approximating the Statistical Properties of Elasticities." *Review of Economics and Statistics* 68(1986):715–719. doi: 10.2307/1924536.

Kroeker, K. J., R. L. Kordas, R. N. Crim, and G. G. Singh. "Meta-Analysis Reveals Negative yet Variable Effects of Ocean Acidification on Marine Organisms." *Ecology Letters* 13(2010):1419–1434. doi: 10.1111/j.1461-0248.2010.01518.x.

Lewis, E. D., D. W. R. Wallace, and L. J. Allison. "Program Developed for CO_2 System Calculations." 1998.

Moschini, G., and A. Vissa. "A Linear Inverse Demand System." *Journal of Agricultural and Resource Economics* 17(1992):294–302.

Narita, D., K. Rehdanz, and R. S. J. Tol. "Economic Costs of Ocean Acidification: A Look into the Impacts on Global Shellfish Production." *Climatic Change* 113(2012):1049–1063. doi: 10.1007/s10584-011-0383-3.

O'Donnell, M. J., M. N. George, and E. Carrington. "Mussel Byssus Attachment Weakened by Ocean Acidification." *Nature Climate Change* 3(2013):587–590. doi: 10.1038/nclimate1846.

Park, H., W. N. Thurman, and J. E. Easley Jr. "Modeling Inverse Demands for Fish: Empirical Welfare Measurement in Gulf and South Atlantic Fisheries." *Marine Resource Economics* 19(2004):333–351.

Ries, J. B., A. L. Cohen, and D. C. McCorkle. "Marine Calcifiers Exhibit Mixed Responses to CO2-Induced Ocean Acidification." *Geology* 37(2009):1131–1134. doi: 10.1130/G30210A.1.

Sabine, C. L., R. A. Feely, N. Gruber, R. M. Key, K. Lee, J. L. Bullister, R. Wanninkhof, C. S. Wong, D. Wallace, B. Tilbrook, F. J. Millero, T. H. Peng, A. Kozyr, T. Ono, and A. F. Rios. "The Oceanic Sink for Anthropogenic CO2." *Science* 305(2004):367–371. doi: 10.1126/science.1097403.

Thong, N. T. "An Inverse Almost Ideal Demand System for Mussels in Europe." *Marine Resource Economics* 27(2012):149–164. doi: 10.5950/0738-1360-27.2.149.

UC Davis Department of Chemistry. *ChemWiki: The Dynamic Chemistry Textbook*. 2011. Available online at http://ChemWiki.ucdavis.edu/.

van Heuven, S., D. Pierrot, E. Lewis, D. W. R. Wallace, and J. W. B. Rae. "MATLAB Program Developed for CO2 System Calculations." 2009.

van Vuuren, D. P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G. C. Hurtt, T. Kram, V. Krey, J. F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S. J. Smith, and S. K. Rose. "The Representative Concentration Pathways: An Overview." *Climatic Change* 109(2011):5–31. doi: 10.1007/s10584-011-0148-z.

Wittmann, A. C., and H.-O. Pörtner. "Sensitivities of Extant Animal Taxa to Ocean Acidification." *Nature Climate Change* 3(2013):995–1001. doi: 10.1038/nclimate1982.

Wong, K. K. G., and K. R. McLaren. "Specification and Estimation of Regular Inverse Demand Systems: A Distance Function Approach." *American Journal of Agricultural Economics* 87(2005):823–834. doi: 10.1111/j.1467-8276.2005.00772.x.