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Welfare Impacts of Ocean Acidification: An Integrated Assessment Model of the US Mollusk Fishery

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Abstract

As atmospheric carbon dioxide (CO_2) concentrations increase, the world's oceans are absorbing CO_2 at a faster rate than at any time in the past 800,000 years. While this reduces the amount of the most prevalent greenhouse gas in the atmosphere it also causes changes in seawater chemistry, collectively known as ocean acidification. One of the known ecological impacts of ocean acidification is a reduced ability of some marine calcifiers to form shells and skeletons. Mollusks and reef building corals are particularly vulnerable. Understanding how these biophysical impacts affect social welfare is a critical step in crafting and evaluating policies that reduce CO_2 emissions. There is an extensive body of literature estimating the economic impacts of climate change but very little research has been done on how ocean acidification could affect social welfare. This paper proposes an integrated biogeochemical-economic model to estimate the social welfare impacts of ocean acidification in the US mollusk fishery. To demonstrate the model two pathways for global greenhouse gas emissions are compared: a baseline path and a policy path in which CO_2 and other greenhouse gas emissions are reduced. These pathways provide input for integrated earth systems models, generating forecasts of changes to sea water chemistry and mollusk production. A two-stage demand system estimates the utility function parameters needed to calculate compensating variation for avoided increases in the prices of oysters, scallops, clams and mussels. The model estimates annual compensating variation for the mitigation path relative to baseline conditions.

JEL Classification: C33, Q22, Q54, Q57

Key Words: Ocean acidification, integrated assessment model, demand system estimation

1. Introduction

The ocean is the Earth's largest sink of atmospheric carbon dioxide (CO_2) and has absorbed about one third of the anthropogenic CO_2 emissions over the past 200 years (Sabine et al 2004). The increasing rate at which the ocean is absorbing CO_2 is causing a number of changes to seawater chemistry, collectively known as ocean acidification. CO_2, when absorbed into the ocean, acts as an 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 et al 2009). In addition to species that humans value directly, many important plankton species that form the base of the marine food web are also calcifiers and have exhibited vulnerability to falling pH and Ω_A (Guinette and Fabry 2008).

Regulations and agreements that reduce carbon dioxide emissions, such as fuel economy standards in the US or the European Union's 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 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 revenues in the mollusk fishery (Cooley and Doney 2009; Narita et al 2011) and ecosystem services provided by coral reefs (Brander et al 2009).

Welfare impacts of climate change are estimated using integrated assessment models (IAMs) which link models of greenhouse gas (GHG) emissions, Earth systems dynamics, and economic damages from temperature change. Policy makers would benefit from analogous models of ocean acidification impacts in order to consider more comprehensive measures of damages from CO_2 emissions. It is useful to think of an *impact pathway* through which CO_2 and other greenhouse gas emissions affect social welfare.

This paper develops an integrated biogeochemical-economic model to simulate the impact pathway in figure 1 and project the potential impacts of ocean acidification on the US market for oysters, scallops, clams, and mussels. The integrated model forecasts changes in consumer welfare through the end of this century using the following models and data:

1. Exogenous pathways for GHG concentrations and radiative forcing are used to project sea surface temperatures (SST) under two different policy scenarios
2. Exogenous pathways for CO_2 concentrations and the SST projections from Step 1 are used as inputs to an ocean carbon model that calculates changes in the aragonite saturation state Ω_A
3. Species-specific growth rate responses to falling Ω_A provide the biological impacts
4. A Cobb-Douglas production function with environmental quality as an input allows the derivation of the evolution of the price vector
5. A two-stage demand system estimates the parameters of a representative household's expenditure function that accounts for income changes and substitution between mollusks and other meats
6. The estimated expenditure function is used to calculate compensating variation between two alternative policy paths and the resulting evolution of the mollusk price vector

The two-stage budgeting model allows estimation of total income and price elasticities so that mollusk expenditures can be modeled as functions of population and household income growth. The almost ideal (AI) demand system, estimated in the second stage, allows substitution among mollusks that exhibit different biological responses, and thus price changes, under the same set of ecological conditions while the first stage expenditure model accounts for cross-price effects with other consumption categories. The utility theoretic demand model allows estimation of social welfare changes as opposed to previous economic studies of ocean acidification that project revenue losses. Estimated annual welfare impacts of the lower emissions path are initially small: about seven cents per household, on average. That figure grows to nearly two dollars per household by the end of this century as demand for mollusks increases and the divergence of projected ecological effects of ocean acidification between the policy and baseline paths increases. The estimated present value of compensating variation for the emission reduction examined in this paper is more than 700 million dollars when discounted at 5% through the year 2100.

This model can be expanded to estimate welfare impacts to global markets for mollusks and finfish given sufficient market data and ecological response functions. Market and non-market impacts to coral reefs are also needed for a comprehensive estimate of the potential economic impacts of ocean acidification. This paper lays the groundwork for such an estimate by introducing an integrated biogeochemical-economic model capable of estimating utility theoretic measures of welfare gains from mitigating the some of the anticipated consequences of ocean acidification.

2. **The biogeochemical model**

The biogeochemical model simulates the impact pathway from GHG emissions to the biological responses of the four mollusks species of interest to this model. Exogenous projections of CO_2 and other GHG emissions and the resulting radiative forcing are taken from the representative concentration pathways (RCP; Meinshausen et al 2010) which were generated for the IPCC Fifth Assessment Report. The model developed in this paper will operate on two of the RCP scenarios, treating the high-emissions pathway (8.5 w/m^2 radiative forcing in 2100) as the baseline and the medium-high pathway (6 w/m^2 radiative forcing in 2100) as the projected policy outcome (figure 2).

2.1 Sea surface temperature

The relationship between atmospheric CO_2 concentrations and ocean acidification is described, in part, by Henry's Law, "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." However, when temperature is not constant the relationship changes and, in fact, as seawater gets warmer with climate change it will absorb less CO_2 from the atmosphere. So in addition to the pathways for atmospheric CO_2 concentrations, which are equivalent to pCO_2, the surface seawater temperature (SST) is also required for accurate forecasts of Ω_A.

To forecast sea surface temperature I use the simple upwelling diffusion energy balance model of Baker and Roe (2009). 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. The resulting temperature of the surface layer (as well as the temperature anomaly) will depend on the initial value for SST. To generate a single representative starting value for SST, I calculate a market value-weighted 10 year average for the coastal regions of the US where mollusks are harvested and cultured. Table 1 shows the annual average surface seawater temperature for the coastal regions of the US (NOAA National Oceanographic Data Center) over the past 10 years and how much of the US mollusk harvest value each region contributed in that time. The time path of temperature changes for each of the RCP emissions scenarios are added to the weighted average of SST to generate representative time paths of SST for the coastal regions of the US (panel A in figure 3).

2. 2 Ocean Carbon Chemistry

With projections of pCO_2 and SST I can forecast changes in seawater chemistry using the ocean carbon model CO2SYS (Lewis and Wallace 1998; van Heuven et al 2011). The CO2SYS program performs calculations relating parameters of the CO_2 system in seawater. The program uses two of the four measureable parameters of the CO_2 system [total alkalinity, total inorganic CO_2, pH and, pCO2] to calculate the two unknown parameters and Ω_A at a given SST. The RCP scenarios and the ocean heat uptake model of Baker and Roe have provided me with time paths for pCO_2 and SST. To complete the set of required inputs I need an initial value for either total alkalinity or total inorganic carbon after which values will be determined within the model. I chose total inorganic carbon and used the CO2SYS model to calibrate that number to observed pCO2 and pH levels in the year 2010. The resulting time paths for Ω_A under the baseline and policy paths are shown in panel B of figure 3.

2.3 Mollusk responses to ocean acidification

As the ocean absorbs more CO_2 from the atmosphere the carbon equilibrium in seawater is shifting toward CO_2 and away from carbonate ion (CO_3^{2-}). The carbonate ion is a critical building block for calcium carbonate shells and skeletons. Decreasing availability of carbonate ion will make it more difficult and eventually impossible for some marine calcifiers to form shells and skeletons (Gazeau et al 2007).

The rate at which marine mollusks are able to build shells is not necessarily an economically relevant measure of ocean acidification's impacts. Consumers care about what is inside the shell and how much it costs. More relevant measures would be how tissue growth and population dynamics, such as reproduction and predation, are affected. Unfortunately no empirical studies have examined these impacts and so studies of shell growth under falling Ω_A provide the only empirical relationships between ocean acidification and mollusk production. Within that body of literature Ries et al (2009) provide the most useful results for economic analysis.

Ries et al (2009) observe the response of different species of various age classes[1] to changing Ω_A levels in controlled experiments. Eighteen different calcifying species were observed for 60 days at four different levels of Ω_A representing current conditions and two, three, and 10 times preindustrial atmospheric CO_2 concentrations. Using regression Ries et al. test several functional forms, finding that

[1] The fact that various age classes were observed is important because the results can be interpreted as average changes over the life time of each species.

over the range of Ω_A observed, growth of the eastern oyster and bay scallop exhibited approximately linear relationships with Ω_A. Hard clams were largely unaffected by the increase to twice preindustrial levels but further increases caused a precipitous decrease in growth rates. Blue mussels did not show any statistically significant response to changes in Ω_A even when increased to levels corresponding 10 times the preindustrial CO_2 concentration. Table 1 summarizes the Ries et al results for the four types of mollusk in the demand model. The regression results in table 2 provide the link in this integrated model between the geochemical and biophysical components. Each of the empirical response functions operates on the projected levels of Ω_A to forecast changes in shell growth rates shown in figure 4.

3. Mollusk production and evolution of prices

The effect that ocean acidification may have on each mollusk price will be inferred from a production function for a perfectly competitive industry that includes environmental quality as an input. This approach has been used to estimate welfare impacts of habitat destruction on fisheries (e.g. Ellis and Fisher, 1987; Barbier, 1994; Barbier and Strand, 1998) and air quality on agriculture (Kopp and Krupnick, 1987). For each mollusk type *i*, I assume that production can be represented by the Cobb-Douglas form

$$q_i = A_i X_i^{\beta_i} E^{\gamma_i} ,$$

where X is an input to production (e.g. harvest effort), E is a measure of environmental quality, and A, β and γ are parameters. In this application E would be changing over time but I omit the time subscripts on all arguments to simplify notation. The solution to the static profit maximization problem yields the cost function

$$C_i = w_i \left(\frac{q_i}{A_i E^{\gamma_i}} \right)^{\frac{1}{\beta_i}}$$

where w_i is the unit cost of input X_i. Differentiating with respect to q_i provides the marginal cost function for mollusk *i*

$$\mathrm{MC}_i = \frac{\partial C_i}{\partial q_i} = \frac{w_i}{\beta_i} \left(\frac{1}{A_i \mathrm{E}^{\gamma_i}} \right)^{\frac{1}{\beta_i}} q_i^{\frac{1-\beta_i}{\beta_i}} , \tag{1}$$

which, under perfect competition, a reasonable assumption in the US mollusk markets, will also be equal to price. The elasticity of price for mollusk *i* to changes in environmental quality is therefore found by taking the natural log of (1) and differentiating with respect to ln(E), $\frac{\partial \ln P_i}{\partial \ln E} = -\frac{\gamma_i}{\beta_i}$.

The parameters β and γ are the output elasticities of X and E. Since X is the only material input to production, β indicates the return to scale. Identification of γ will depend on how environmental quality is defined in the model and the biological response of each mollusk to that metric. In principle, this is an empirical question: How is the production of clams, oysters, scallops and mussels affected by falling Ω_A levels, holding other inputs to production constant? Unfortunately for the researcher (not so for the mollusks), the environmental conditions of interest have not been observed and so the data required to answer this question directly are not available. Instead, following Cooley and Doney (2009), I assume that changes in production for each type of mollusk, holding other inputs constant, are proportional to changes in the calcification rate so that, $\frac{\partial \ln q_i}{\partial \ln g_i} = 1$. If the metric for environmental quality in the production function is defined as the calcification rate for each mollusk, then

$\frac{\partial \ln q_i}{\partial \ln E} = \frac{\partial \ln q_i}{\partial \ln g_i}$ and $\gamma = 1$ so that the evolution of the price vector is described by

$$\frac{\partial \ln P_i}{\partial \ln g_i} = \frac{1}{\beta_i} . \quad (2)$$

β will be set equal to 1 for all i implying constant returns to scale in each mollusk fishery and unitary price elasticity with respect to growth rates.

4. **Two-stage demand model and welfare**

The two stage budgeting approach models consumption as though households first allocate income among expenditure groups and then decide how much of each group's allocation to spend on individual commodities. Estimation requires that utility be weakly separable in these commodity groups so that a price change for a given commodity only affects consumption of commodities in other groups through the first stage allocation process, and that the proportional change in demand will be the same for each commodity in a group. The advantage of multi-stage budgeting is that it allows identification of total (unconditional) elasticities without having to estimate a complete demand system (i.e. a demand equation for every commodity that households consume). This feature is particularly important for this model because projections of welfare changes will reach the end of this century during which real incomes will grow and mollusk prices will rise. The two stage model allows projected expenditures on each commodity group to respond to income and prices based on elasticities estimated in the first stage. Those commodity group expenditures and the coefficients of the second stage demand system are used to calculate welfare impacts from expected changes in the mollusk price vector.

4.1 First stage expenditure model

To estimate an expenditure function for the mollusk commodity group I estimate a linear household expenditure model that is a function of disposable income, a price index for mollusks, logged prices for substitutes and other conditioning variables. It is common to estimate a system of expenditure functions in the first stage (e.g. Edgerton 1997, Jorgenson et al 1988) but because I am only interested in expenditures on mollusks, expenditures on other commodity groups are not modeled here. The first stage is a linear expenditure model with the functional form

$$\ln x = \theta_0 + \varepsilon_y \ln y + \eta_P \ln P + \sum_{k=1}^{m} \theta_k \ln\left(p_k\right) + \sum_{j=m}^{s} \theta_j z_j + e \,, \qquad (3)$$

where ε_y and η_P are the income and price elasticities of mollusk expenditures, θ is a vector of parameters, y is a vector of average household disposable income, p is a matrix of prices for mollusk substitutes, z is a matrix of conditioning variables, and e is a vector of *iid* normally distributed errors. Quantity and prices are time series data but I suppress the time subscript here to simplify notation. The form of the mollusk price index *lnP* is taken from the almost ideal demand model estimated in the second stage and requires coefficients estimated in that stage α_0 and α_k,

$$\ln P = \alpha_0 + \sum_{k}^{n} \alpha_k \ln\left(p_k\right) + \frac{1}{2}\sum_{j=1}^{n}\sum_{k=1}^{n} \ln\left(p_k\right)\ln\left(p_j\right) \qquad (4)$$

Because coefficients from the demand system enter the price index equation the second stage must be estimated before the first. While this may seem counterintuitive, or at least odd, it has no practical implications on estimation or the results.

4.2 Second stage demand system

The correct welfare measure to use when evaluating mitigation policy that will reduce prices relative to their baseline path is compensating variation (Bockstael and McConnel, 1983). To estimate compensating variation (CV) from an empirical demand system, the form of the demand functions must be derived in a utility theoretic framework so that parameters of the expenditure function or indirect utility function can be recovered. This model uses aggregate consumption data to model household expenditure decisions, focusing attention on the aggregation properties of the underlying preferences. The price indifferent generalized logarithmic (PIGLOG) class of preferences permits exact aggregation over consumers (Muellbauer 1976) allowing inference on household optimization using aggregate data. The PIGLOG expenditure function is of the form

$$\ln e\left(u, p\right) = a(p) + ub(p) \tag{5}$$

where u is the utility level and p is a vector of prices. Using the AI demand system (Deaton and Muellbauer 1980) specification for the log expenditure function

$$a\left(p\right) = \alpha_0 + \sum_{j=1}^{n} \alpha_j \ln p_j + \frac{1}{2}\sum_{j=1}^{n}\sum_{k=1}^{n} \phi_{jk} \ln p_j \ln p_k$$

$$b\left(p\right) = \psi_0 \prod_{k}^{n} p_k^{\psi_k} \ ,$$

where the vectors ϕ and ψ are parameters. Invoking Shephard's lemma yields the estimable system of expenditure shares (see Deaton and Meullbauer for the complete derivation)

$$w_i = \frac{p_i q_i}{x} = \alpha_i \sum_{j=i}^{n} \phi_{ij} \ln\left(p_j\right) + \psi_i \ln\left(\frac{x}{P}\right)$$

Aggregation conditions imply $\sum_i^n \alpha_i = 1$, $\sum_i^n \phi_{ij} = 0$ and $\sum_i^n \psi_i = 0$, while homogeneity and symmetry require $\sum_j^n \phi_{ij} = 0$ and $\phi_{ij} = \phi_{ji}$. Conditional on a fixed level of total expenditures *x,* the expenditure elasticities of demand are

$$\varepsilon_{i|x} = 1 + \frac{\psi_i}{w_i} \tag{6}$$

and the conditional uncompensated price elasticities are

$$\eta_{ij|x} = \delta_{ij} + \frac{\gamma_{ij}}{w_i} - \frac{\beta_i \alpha_i}{w_i} - \frac{\beta_i}{w_i} \sum_{j=1}^{n} \gamma_{ij} \ln p_j \,, \tag{7}$$

where $\delta_{ij} = -1$ if $i = j$ and $\delta_{ij} = 0$ if $i \neq j$ (Fan et al 1995).

Combining the results of the first and second stage models allows estimation of total (unconditional) elasticities. Fan et al (1995) also estimate a two-stage demand system and show that the total (unconditional) income elasticity commodity *i* is

$$\varepsilon_i = \varepsilon_{i|x} \varepsilon_y \tag{8}$$

and the total (unconditional) price elasticity for commodity *i* is

$$\eta_{ij} = \eta_{ij|x} + \varepsilon_{i|x} w_j \left(1 + \eta_P\right). \qquad (9)$$

4.3 Compensating variation

Realizing that a utility maximizing consumer will ensure $e(u,p) = x$ expression (5) can be inverted for the indirect utility function

$$u(x,p) = \frac{\ln(x) - a(p)}{\prod_k p_k^{\psi_k}}.$$

If the vector of prices is unchanged and the indirect utility function is plugged into expression (5), after cancelling terms, the result is simply $\ln e(u,p) = \ln x$. However if p^0 represents the original vector of prices and p^1 is a new price vector, then substituting $u(x,p^0)$ into $e(u,p^1)$ will yield the minimum expenditure level required to reach the original level of utility when facing the new vector of prices, so that

$$\ln e(u,p^1) = a(p^1) + \frac{\ln(x) - a(p^0)}{\prod_k \left(p_k^0\right)^{\psi_k}} \prod_j \left(p_j^1\right)^{\psi_k}.$$

The difference between the original level of expenditures x and the minimum level required to achieve the same utility under a new set of prices $e(u,p^1)$ is the compensating variation (CV)

$$CV = x - \exp\left[a\left(p^1\right) + \frac{\ln\left(x\right) - a\left(p^0\right)}{\prod_k \left(p_k^0\right)^{\psi_k}} \prod_j \left(p_j^1\right)^{\psi_j} \right]. \quad (10)$$

5. Data and Methods

The two stages of the budget allocation demand model rely on similar data except that in the first stage mollusk expenditures are aggregated and household disposable income is included as an independent variable. Domestic consumption of mollusks is calculated using monthly landings data from 1990 through 2010 and subtracting net exports of live or fresh mollusks (National Marine Fisheries Service). Dockside prices are used because of the lack of data on retail prices and linear interpolation of quarterly observations of disposable income provides monthly observations (Bureau of Economic Analysis). Monthly wholesale prices for beef, chicken, and pork are used as conditioning variables in the first stage expenditure model. And because the harvest and consumption of most mollusks varies seasonally, a cosine function that peaks in December and reaches a minimum in June is used to estimate both stages of the model. Finally, a logged year index captures a diminishing time trend that is orthogonal to income and price effects.

The first stage expenditure equation is estimated via ordinary least squares. The second stage demand system is estimated using nonlinear seemingly unrelated regression (NLSUR) while constraining the coefficients on logged prices to satisfy symmetry restrictions. Only n-1 equations of the system are estimated directly to avoid singularity of the error variance-covariance matrix. The homogeneity and adding-up restrictions are used to recover the coefficients of the n^{th} equation.

Finally, in order to forecast expenditures on the mollusk commodity group via equation 3, I use the 2009 Stanford Energy Modeling Forum's (EMF 22) projections of US gross domestic product (GDP) and population from the IMAGE modeling group and assume that households will maintain their recent 10-year average of 2.57 people and disposable income being 70% of GDP. The resulting forecast of households and disposable income is summarized in table 4.

6. Results

In this section I present the results of the two-stage demand model and use them to forecast total mollusk expenditures for the income and baseline price projections. The projected baseline mollusk expenditures and time paths of the mollusk price vector are then used in expression (10) to calculate annual compensating variation for the emissions reductions realized by moving from the high RCP emissions path to the medium-high path.

6.1 Estimation results

The log-log specification of the first-stage expenditure model means that the coefficients on income and prices (Table 5) can be interpreted as elasticities for total expenditures on the mollusk commodity group. The first-stage income and price elasticities are of the expected sign, with only the chicken cross price elasticity being statistically insignificant. Beef and pork appear to be substitutes for mollusks so far as increases in those prices are correlated with an increase in expenditures on the mollusk group. Over the span of the time series, holding all else equal, there has been a negative but diminishing trend in mollusk expenditures. And though different types of mollusks in the commodity group have different harvesting seasons, there is a statistically significant seasonal cycle in total expenditures.

One of the implications of the AI specification of the second stage demand system is that the magnitude, statistical significance and sign of an individual coefficient do not have practical meaning. For example, a positive coefficient on the log of own-price does not imply that price has positive effect on the quantity consumed. The results of the second stage AI demand system are reported in table 6, but discussion should be reserved for price and expenditure elasticities which are functions of multiple parameters (equations [6] through [9]). To conduct inference on the results of the second stage model, I simulate distributions for the conditional price and expenditure elasticities via bootstrapping. Table 7 reports the means and standard deviations of the bootstrapped sample based on 5,000 draws of the second stage coefficients. These elasticities indicate how consumption of each type of mollusk tends to change in response to a price increase *while holding total mollusk expenditures fixed*. Three out of the four own-price elasticities have the expected sign and are statistically significant. The conditional demand for mussels does not appear to be responsive to price. This pattern is repeated in the expenditure elasticities; the demands for oysters, scallops, and clams tend to increase with total mollusk expenditures but the demand for mussels does not.

Total price and income elasticities draw on the results of the first and second stage models and can differ substantially from the conditional elasticities which are based on the second stage results alone. Total elasticities will generally be smaller in magnitude than conditional elasticities because expenditures on the commodity group will adjust with prices and income. Table 8 reports summary statistics of bootstrapped samples of the total elasticities based on 5,000 draws of the first and second stage coefficients. Again, mussel demand is not responsive to own-price changes but its income elasticity is positive, albeit small, and statistically significant. The income elasticities for oysters, scallops, and clams are also statistically significant.

6.2 Simulation and welfare results

The price and income elasticities are not used directly in the welfare calculation but they are a convenient way to judge the identification strategy of the two-stage demand model. Instead, the first stage is used to forecast total mollusk expenditures as a function of disposable income and the baseline price index for mollusks. The coefficients of the second stage are used in the welfare calculations and to identify the price index. However, a necessary input into both the expenditure and welfare simulations is the time paths for mollusk prices. Using the growth rate changes of figure 4 and the price evolution equation (2), baseline and policy price projections are plotted in figure 5. Recall Ries et al (2009) did not observe a response from mussels to falling Ω_A, so I assume their dockside price will remain constant at the recent 10-year average of $0.72 per pound of meat and is not plotted in figure 5.

Evaluating equation (4) along the baseline price projection vector provides the baseline price index which, along with the household income projections in table 4, is needed to forecast household expenditures on mollusks. Assuming the prices of beef, chicken and pork remain constant in real terms, baseline mollusk expenditures are expected to increase with income but not as quickly as the income elasticity ε_y alone would suggest. There is also downward pressure on mollusk expenditures from the rising prices via the price index elasticity η_P and the logged time trend θ_4. However, baseline utility is falling over time so expenditures required to maintain baseline utility when prices increase more slowly will also decrease, all else being equal. Figure 6 plots household minimum expenditures on mollusks required to achieve baseline utility and shows that is indeed the case here for much of the time horizon. The vertical distance between these two curves is the undiscounted annual measure of CV at a given point in time. Table 9 summarizes the results of the welfare calculation using equation (10) for compensating variation. Annual CV for households and the US as a whole are both increasing because the price differential between the baseline and policy cases grows over time, but the total CV for the US grows at a faster rate due to population growth. The present value of CV is found using a 5% discount rate.

7. Conclusion

It is not yet clear how estimates ocean acidification damages will compare with those of climate change. The goal of this line of research is to remove ocean acidification from the list of "unquantified benefits" of reducing CO_2 emissions. Filling this gap in the literature and, by extension, analysis of domestic and international carbon policy should be a research priority. While the estimates produced here reflect just a fraction of total damages from ocean acidification, the methodology can be used to value market impacts to global finfish and shellfish markets.

One major caveat is that the geochemical, biological, and economic models that form the integrated model are not equal in their reliability. The two-stage demand system is based on well-established methods and estimated with reliable data. Likewise, the ocean carbon model is based on well-understood deterministic relationships relating atmospheric CO_2 concentrations to aragonite saturation levels. The projected time paths for CO_2 concentrations and sea surface temperature are based on sophisticated equilibrium and climate models but are, nonetheless, long-term projections involving highly uncertain variables. The Ries et al. study relating changes in mollusk growth rates to falling Ω_A levels is the best of its kind for the purposes of this study because it (1) examines the most popular species in US markets (2) uses levels of pCO_2 and Ω_A that we are likely to witness this century and (3) observes the subjects over a 60-day period. Many studies of this type examine non-harvested species under extreme conditions and do so over a period of just a few hours.

The most tenuous link in the integrated model is the relationship between changes in growth rates to the evolution of mollusk prices. This study presumes, via Cobb-Douglas production with environmental quality as an input, that changes in growth rates will have a proportional effect on the marginal cost of mollusk production. Ideally, an empirical study of how falling Ω_A affects the harvest and culture of mollusks would inform the modeled relationship. The relationships assumed here serve as placeholders until more data are available.

When evaluating domestic policies that affect greenhouse gas emissions the US government uses a measure that reflects the global benefits of mitigating climate change (Social Cost of Carbon TSD

2010). The most immediate and useful extension of this work is to develop a global measure of welfare impacts in markets for mollusks. Over the past ten years 12 countries consumed more than 90% of the global shellfish harvest (FAO Fisheries Database), so it is possible to quantify the vast majority of benefits by focusing on just a dozen countries. The direct impact to shellfish markets is just one of the three categories of impacts to consider. Direct impacts to coral reefs will include market and nonmarket measures of benefits. Estimating potential impacts to finfish stocks requires modeling of trophic interactions and migration that, while possible on a local level, is not currently feasible for a fishery as large as the US market.

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Figures

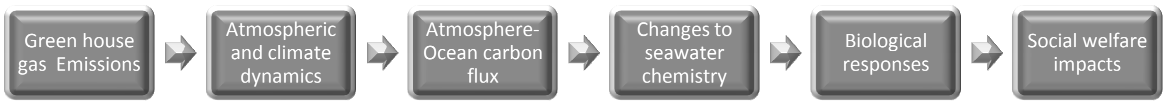

Figure 1 Ocean Acidification Impact Pathway

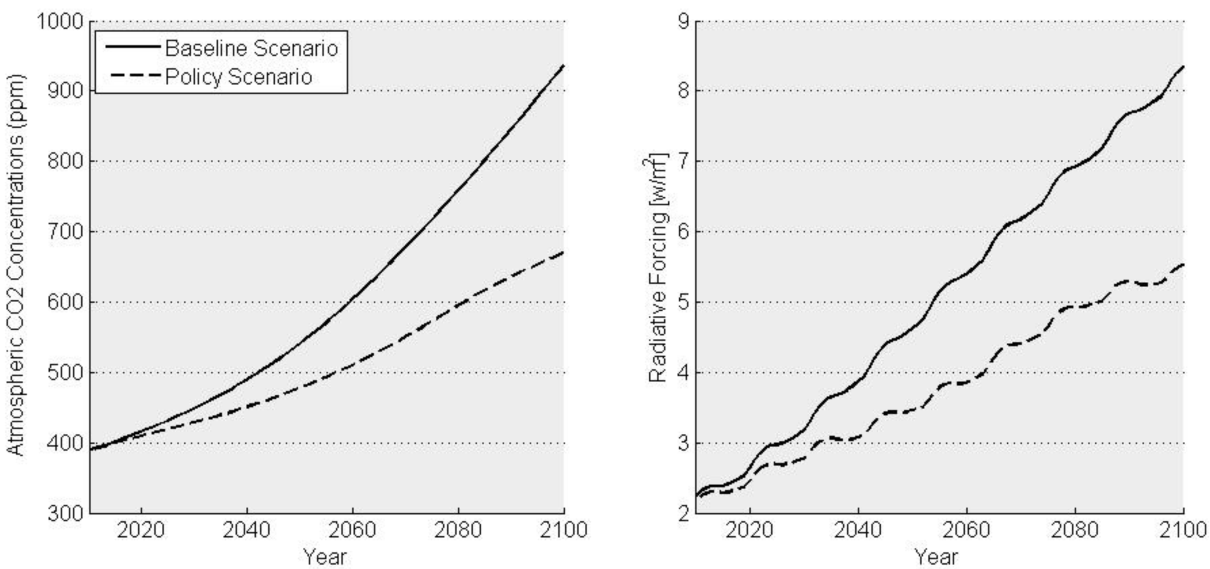

Figure 2 RCP CO_2 concentration and radiative forcing forecasts

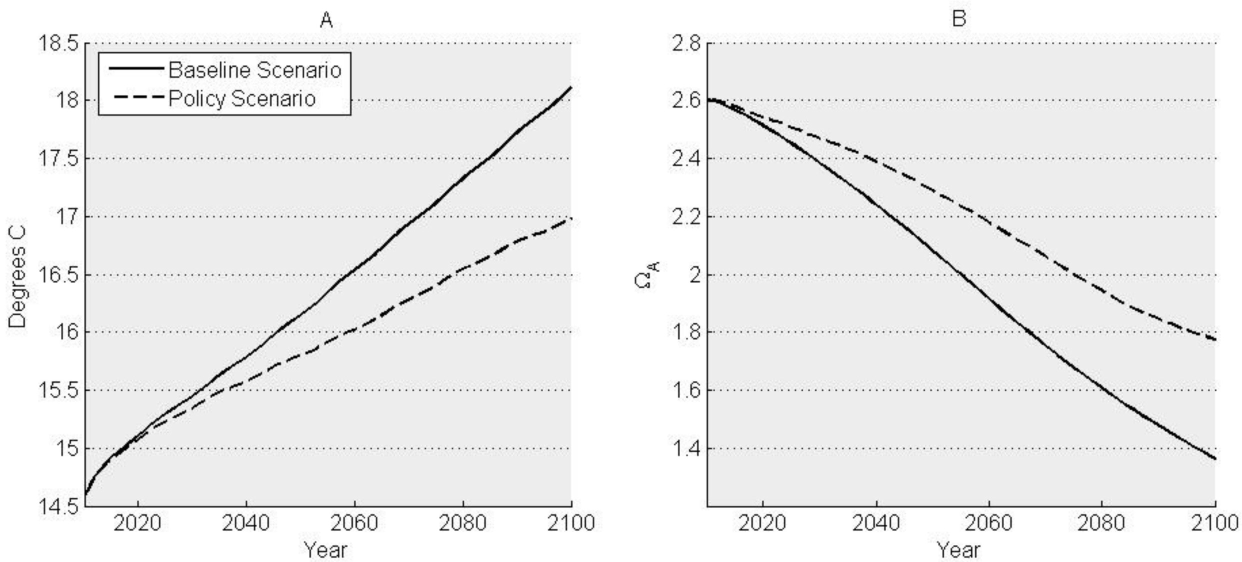

Figure 3 Projections of SST and Ω_A

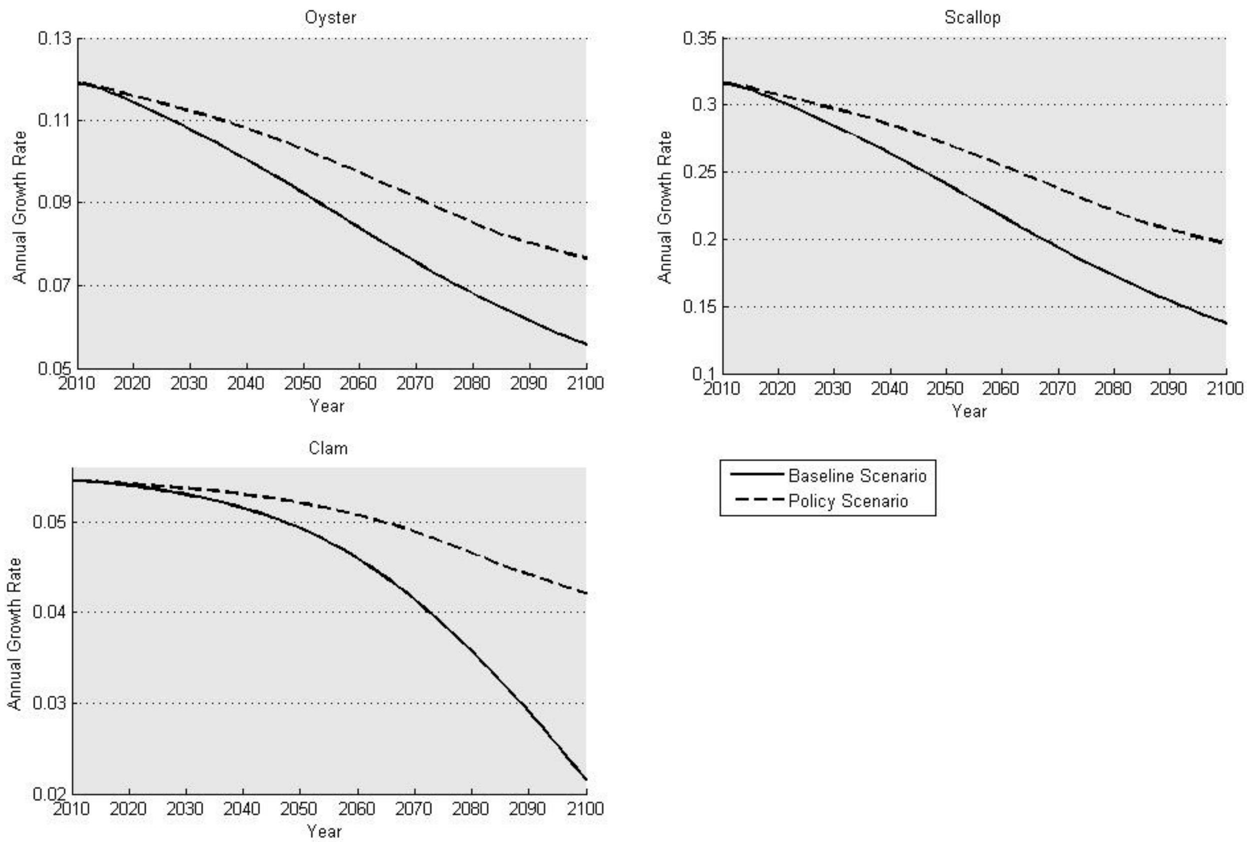

Figure 4 Projections of annual mollusk growth rates

* Ries et al (2009) observed mollusk growth over a 60-day period. The growth rates shown in this figure are estimated with the regression equations in table 1 and then adjusted to reflect annual growth rates.

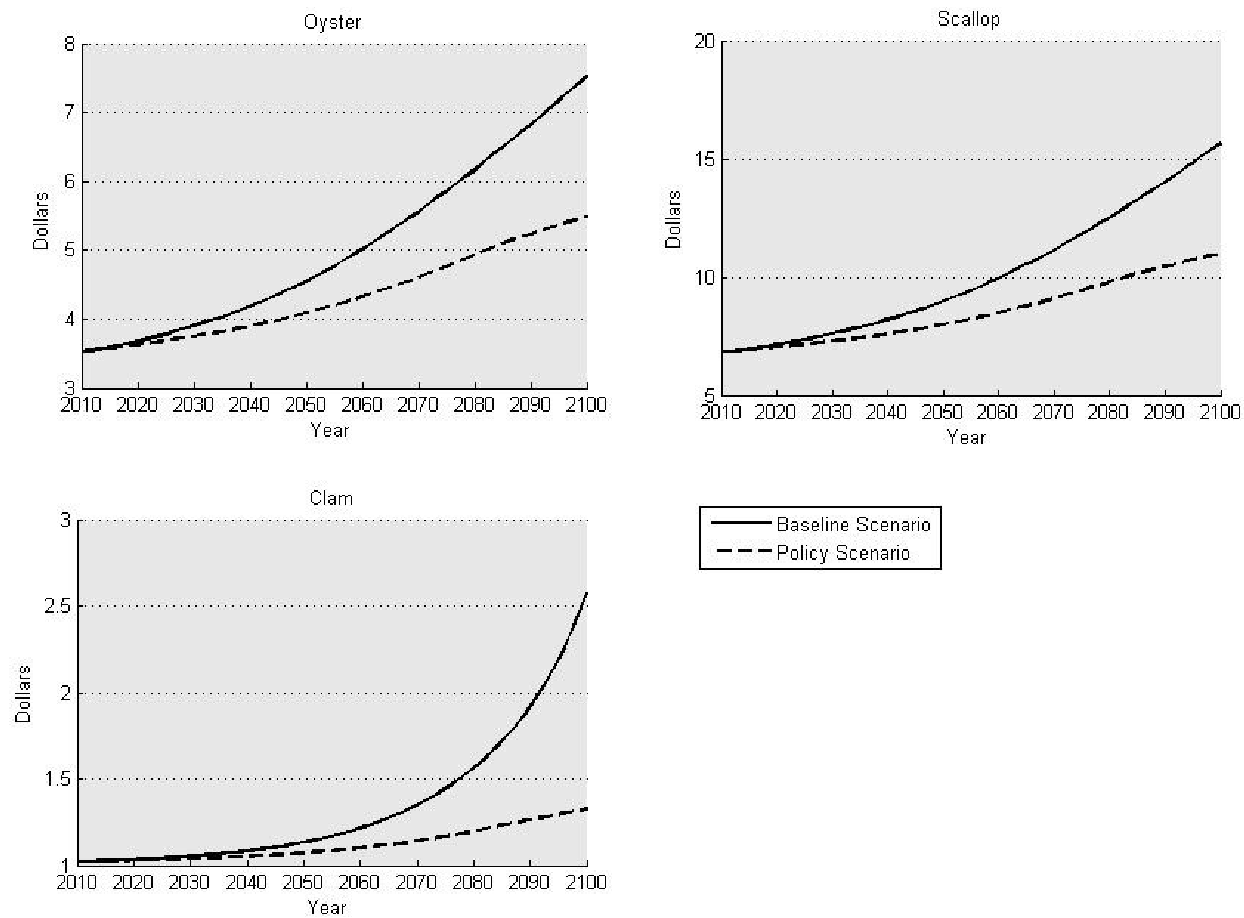

Figure 5 Mollusk price projections

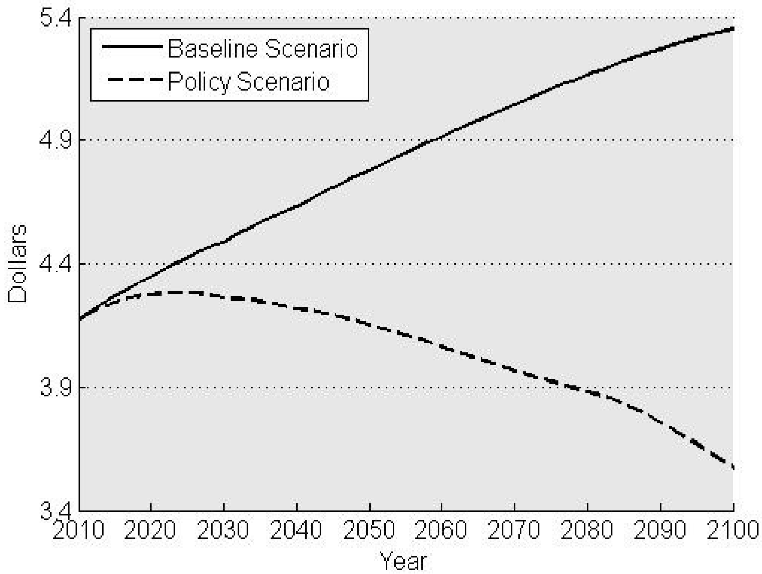

Figure 6 Household expenditures required to reach baseline utility

Tables

Table 1 Market value-weighted average of initial SST

US Coastal Region	Average Proportion of Mollusk Market Value	10-year Average SST (C)
New England	0.48	11.45
Mid-Atlantic	0.24	15.12
South Atlantic	0.03	22.18
Gulf of Mexico	0.15	23.45
North Pacific	0.10	11.45
Market value-weighted average initial SST		14.52

Table 2 Growth rate responses to different levels of ΩA (Ries et al 2009)

Mollusk Name	Regression Equation	R^2	Expected 60-day % change in weight		
			Ω_A=2.13 Current pCO_2	Ω_A=1.53 2 x Preindustrial	Ω_A=1.13 3 x Preindustrial
Eastern Oyster	$g_1 = 0.84\Omega_A - 0.23$	0.76	2.019	1.515	1.179
Bay Scallop	$g_2 = 2.73\Omega_A - 0.97$	0.34	6.018	4.596	3.648
Hard Clam	$g_3 = -10.3\,e^{2.1\Omega_A} + 0.94$	0.81	0.962	0.458	-0.254
Blue Mussel	No response	-	3.7	3.7	3.7

Table 3 Summary of demand model data

Variable	Description	Mean	Std Dev	Min	Max
$w_{scallops}$	scallops expenditure share	0.547	0.136	0.255	0.883
$w_{oysters}$	oysters expenditure share	0.214	0.096	0.057	0.513
w_{clams}	clams expenditure share	0.211	0.089	0.021	0.449
$w_{mussels}$	mussels expenditure share	0.029	0.020	0.003	0.111
$p_{scallops}$	scallops dockside price per pound	2.61	0.58	1.62	4.23
$p_{oysters}$	oysters dockside price per pound	5.60	1.29	3.16	9.10
p_{clams}	clams dockside price per pound	0.83	0.26	0.54	2.45
$p_{mussels}$	mussels dockside price per pound	0.58	0.28	0.27	1.84
p_{beef}	beef wholesale price per pound	1.92	0.29	1.47	2.72
$p_{chicken}$	chicken wholesale price per pound	1.14	0.12	0.81	1.49
p_{pork}	pork wholesale price per pound	0.63	0.08	0.49	0.89
lnM	log of mollusk expenditures per 1,000 households	5.69	0.29	4.97	6.19
lnP	AI price index for mollusks	5.83	0.17	5.51	6.35
Y	average household disposable income	68,264	15,445	44,510	95,614
Year	index for year	10.5	5.77	1	20
cos(month)	cosine on month index	0	0.71	-1	1

Table 4 Socioeconomic projections

Year	Household Disposable Income (thousands of dollars)	Households in US (millions)
2010*	86.5	120.1

2020	99.8	131.0
2030	113.0	141.0
2040	126.6	149.0
2050	141.4	155.5
2060	157.3	158.3
2070	174.4	161.4
2080	192.7	163.6
2090	212.5	165.2
2100	233.6	166.4

*Observed (US Department of Commerce Bureau of Economic Analysis)

Table 5 – First stage results

Dependent Variable: log of mollusk expenditures (ln M)			
			n = 240
			R-squared: 0.7077
Variable	Parameter	Coefficient Estimate	Standard Error
ln (y)	ε_y	0.555**	0.255
lnP	η_P	-0.181*	0.107
ln (p_{beef})	θ_1	0.324**	0.161
ln ($p_{chicken}$)	θ_2	-0.065	0.576
ln (p_{pork})	θ_3	0.477**	0.147
ln (year index)	θ_4	-0.100*	0.057
cos (month index)	θ_5	-0.260	0.019
constant	θ_0	0.503	2.483

*   significant at the 90% confidence level

** significant at the 99% confidence level

Table 6 Second Stage Constrained Nonlinear SUR

Dependent variable: expenditure share (w_i)

n = 240

Equation	Variable	Parameter	Estimate	Standard Error
Oysters	constant	α_1	0.222**	0.019
R^2 = 0.967	ln (p_{oyster})	γ_{11}	0.128**	0.013
	ln ($p_{scallop}$)	γ_{12}	-0.088**	0.012
	ln (p_{clam})	γ_{13}	-0.036**	0.009
	ln (p_{mussel})	γ_{14}	-0.004	-
	ln(M/P)	β_1	-0.140**	0.013
	ln (year index)	-	0.072**	0.006
	cos(month index)	-	-0.011*	0.005
Scallops	constant	α_2	0.409**	0.035
R^2 = 0.984	ln ($p_{scallop}$)	γ_{22}	0.078**	0.018
	ln p_{clam})	γ_{23}	0.034**	0.013
	ln (p_{mussel})	γ_{24}	-0.025	-
	ln(M/P)	β_2	0.254**	0.019
	ln (year index)	-	-0.054**	0.009
	cos(month index)	-	0.112**	0.008
Clams	constant	α_3	0.290**	0.019
R^2 = 0.945	ln (p_{clam})	γ_{33}	0.005	0.013
	ln p_{mussel}	γ_{34}	-0.003	-
	ln(M/P)	β_3	-0.084**	0.015
	ln (year index)	-	-0.017*	0.007
	cos(month index)	-	-0.110**	0.006

Mussels	constant	α_4	0.079	-
	ln (p_{mussel})	γ_{44}	0.032	-
	ln(M/P)	β_4	0.030	-

* significant at the 90% confidence level

** significant at the 99% confidence level

Table 7 Conditional Price and Expenditure Elasticities

Quantity \ $	Oysters	Scallops	Clams	Mussels	Expenditures
Oysters	-0.245**	-0.251**	-0.011	0.139**	0.346**
	(0.095)	(0.059)	(0.044)	(0.032)	(0.081)
Scallops	-0.368**	-1.06**	-0.148**	-0.254**	1.470**
	(0.039)	(0.037)	(0.051)	(0.026)	(0.051)
Clams	-0.046	0.280**	-0.845**	0.112**	0.590**
	(0.071)	(0.082)	(0.103)	(0.035)	(0.103)
Mussels	-0.128	-0.868**	-0.082	0.127	-0.048
	(0.127)	(0.105)	(0.123)	(0.106)	(0.127)

* significant at the 90% confidence level

** significant at the 99% confidence level

Table 8 Total Price and Expenditure Elasticities

Quantity \ $	Oysters	Scallops	Clams	Mussels	Income

Oysters	-0.181**	-0.088	0.051	0.147**	0.423*
	(0.086)	(0.074)	(0.050)	(0.031)	(0.241)
Scallops	-0.096**	-0.368**	0.120**	-0.120**	1.83*
	(0.041)	(0.114)	(0.042)	(0.043)	(0.987)
Clams	0.060	0.555**	-0.740**	0.126**	0.733*
	(0.065)	(0.096)	(0.101)	(0.034)	(0.411)
Mussels	-0.136	-0.891**	-0.073	0.127	-0.064
	(0.121)	(0.105)	(0.126)	(0.105)	(0.177)

*   significant at the 90% confidence level

** significant at the 99% confidence level

Table 9 Annual compensating variation

Year	2020	2040	2060	2080	2100	NPV discounted at 5%
Household	$0.07	$0.41	$0.85	$1.28	$1.78	**$4.83**
US (Millions)	$9.6	$61.6	$134.9	$209.8	$295.5	**$734.6**