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ECONOMIC IMPACTS OF OCEAN ACIDIFICATION: A META-ANAYSIS

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ABSTRACT: This paper presents the first comprehensive review and synthesis of studies that forecast economic impacts of ocean acidification. The changes in seawater chemistry resulting from increased carbon dioxide emissions, collectively known as ocean acidification, will have detrimental impacts to marine ecosystem services. Those services include wild capture fisheries, aquaculture, recreation, shoreline protection, and others. The current literature valuing expected impacts to those services is rather thin and tends to focus on mollusk harvesting and aquaculture. Despite the paucity of studies, we divide all relevant estimates into seven additively separable economic sectors to provide the first aggregate estimate of economic damages from ocean acidification at the end of this century. We perform non-parametric bootstrap to characterize the distribution of estimates within each sector and the aggregation across sectors. We also perform meta-regressions to explore whether estimates provided by these studies are generally consistent with expectations based on ocean chemistry and economic theory. We find a global average of per capita annual losses in the year 2100 between $47 and $58 and we find strong evidence that estimates are consistent with expectations given future emissions and socio-economic scenarios that underlie the original studies.

SUBJECT AREA CLASSIFICATIONS: Economic Damages/Benefits, Marine/Coastal Zone Resources, Climate Change

KEYWORDS: Ocean acidification, climate change, meta-analysis, marine ecosystem services

JEL CODES: Q51 Valuation of Environmental Effects

DISCLAIMER

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1. Introduction

Oceans are the largest carbon sink on Earth and as atmospheric concentrations of carbon dioxide (CO2) increase, oceans are absorbing the gas to maintain equilibrium. This balancing act comes at a cost, however. The increased uptake of CO2 affects seawater chemistry in a number of ways, collectively known as ocean acidification (Doney et al. 2009). While the chemistry is well understood, the resulting biophysical impacts to marine organisms and ecosystems are still being discovered (Hilmi et al. 2013, Hall-Spencer and Harvey 2019). In addition to carbon sequestration, oceans provide vital resources and services including food, recreation, and nutrient cycling. Resource economists and ocean scientists have been working to estimate the impact that changes in these services could have on our economy over the next century. This paper provides a comprehensive review of that literature and performs the first quantitative meta-analysis of projected economic impacts from ocean acidification.

Ocean acidification threatens food security, marine ecosystems, and the welfare of coastal communities (Fabry et al. 2008). To ensure efficient allocation of public resources, the costs of climate mitigation and adaptation should be weighed against the benefits of avoiding future damages and the opportunity costs of those resources. This calculus can only be carried out when benefits of mitigation and adaptation are expressed in monetary terms, and requires the most comprehensive estimate of avoided damages possible. Thus far, the literature estimating the potential economic damages of ocean acidification is comprised of studies that focus on narrow sectors of the economy, and at the time of writing, we are not aware of any attempt to synthesize those estimates in a way that provides an aggregate measure of damages. This paper represents the first such attempt to review the existing literature, synthesize the results, and provide the most comprehensive estimate of economic damages from ocean acidification possible, given the current state of the literature.

A significant obstacle to combining estimates across studies is converting them to comparable values. All the studies reviewed provide a monetized estimate for one or more regions or countries, generally for a small sector of the economy, at some point in the future. Some estimates explicitly account for growth in population and real income when estimating economic damages while others ignore those factors. Given the disparity in the underlying assumptions of each estimate, we chose to convert the total economic damages into per capita values using the same socio-economic projections as the original authors for the region of study. Further, we used paired income projections to express those values as a percent of per capita income to facilitate synthesis across countries and regions with vastly different projected economic status. Finally, we divided estimates into additively separable impact categories which allows us to aggregate estimates without double counting impacts. This last exercise reveals how uneven the economic research has been among sectors, driven largely by a similar disparity in the research of the ecological impacts.

We take two approaches to synthesizing the estimates in the literature. The first is a non-parametric bootstrap approach that treats the individual estimates as observations of random variables. Grouping the estimates by sector and calculating the mean and standard deviations within each one provides a characterization of the data without making distributional assumptions. The total damage estimate is then a sum of random variables and the first and second moments of that distribution can be calculated using standard formulas. While our bootstrap approach provides the best synthesis of estimates for aggregation, it is limited in the insight it can provide regarding the relationships between economic damages and features of the underlying studies. To address that question, we perform several meta-regressions that allow us to explore the ways greenhouse gas emission scenarios and socio-economic projections affect the estimates. The lack of estimates in some economic sectors prevents us from using meta-regression to estimate an aggregate damage function, however. Data limitations notwithstanding, we present the results of our exploratory meta-regressions, use the results to draw general conclusions about the literature and provide some guidance for future studies.

The following section reviews the literature estimating the expected economic impacts of ocean acidification, describes the economic sectors we use to aggregate the estimates, and summarizes the studies in each. Section 3 describes our meta-analytic methods and how each approach addresses the structure of the data to minimize bias in our results. Section 4 presents the results of the non-parametric bootstrap and meta-regressions. Section 5 concludes with a discussion of our results and suggestions for authors of forthcoming studies that will provide more robust estimates of economic damages from ocean acidification.

2. Review of the Literature

Using Google Scholar and the EconLit database we found 16 studies that estimate economic impacts from ocean acidification (table 1). Some studies also model damages from warming (e.g. coral bleaching, habitat suitability) and we control for that feature of the studies in our analysis. The key variables required to transform the reported estimates into comparable values are the impact sector(s) being examined, the emissions and socioeconomic scenario(s) underlying the estimates, the year of analysis (year of the damages being estimated), the region for which the impacts are being analyzed, and the currency of the damage estimates.

The exercise of defining economic sectors was simultaneously influenced by the scope of the studies and our desire to combine estimates within a sector and aggregate across them. The economic sectors we defined are commercial mollusk harvest, commercial crustacean harvest, commercial finfish harvest, subsistence and recreational fishing, and coral reef recreation. The mollusk and finfish sectors have estimates that can be further divided into consumer and producer impacts which can be summed without double counting. It is important to distinguish between categories of biological impacts and economic impacts. Coral reefs, for example, provide recreation opportunities and habitat for commercially harvested fish, and some studies we collected provide impact estimates for both. So, while the ecological source of the damages is the same, estimates from those two sectors can be added and should be entered separately. It is also important to note that not all economic damages expected from ocean acidification have been valued in the literature so there are impacts omitted from our analysis. Shoreline protection from coral reefs is one such example.

Table 1 Studies estimating economic impacts from ocean acidification

Author(s) (Year)	Sector(s)	Region(s)	Emissions scenario(s)	Impact year(s)	Included in meta-analysis (Y/N)
Armstrong et al. 2012	Crustaceans, finfish, mollusks	Norway	SRES A2	2060 2110	N
Beck et al. 2018	Coral reef flood protection	Global	RCP 8.5	2100	N
Brander 2009	Coral reef recreation, finfish, mollusks	Global	N/A	2100	N
Brander et al. 2012	Coral reef recreation	Global	SRES A1, A2, B1, B2	2100	Y
Colt and Knapp 2016	Coral reef recreation, subsistence fishing, recreational fishing, finfish	Global	RCP 8.5	2100	Y
Cooley and Doney 2009	Mollusks	US	SRES A1F1, RCP 8.6	2060	Y
Cooley et al. 2012	Mollusks	Global	SRES A2	N/A	N
Fernandes et al. 2017	Finfish, mollusks	England, Northern Ireland, Wales, Scotland	RCP 2.6, 8.5	2045 2095	Y
Lane et al. 2013	Coral reef recreation and existence value	Hawaii, Florida, Puerto Rico	SRES B1, BAU	2030-2100	N
Kite-Powell 2009	Coral reef recreation, finfish	Global	N/A	2200	N
Mangi et al. 2018	Crustacean, mollusks	England, Northern Ireland, Wales, Scotland	SRES A1, B1	2100	Y
Moore 2015	Mollusks	US	RCP 8.5	2100	Y

Narita and Rehdanz 2017	Mollusks	Europe	RCP 8.5	2100	Y
Narita et al. 2012	Mollusks	31 countries and multi-country regions	SRES A1B	2100	Y
Punt et al. 2014	Crustaceans	Alaska	N/A	2100	N
Rodrigues et al. 2013	N/A	Mediterranean Sea	N/A	N/A	N
Seung et al. 2015	Crustaceans	Alaska	N/A	2100	N
Speers et al. 2016	Finfish	Global	RCP 8.5, 6.0	2100	Y

Using population projections specific to the regions and emissions scenarios and the year of the damage estimate, we calculated per capita damages in the year of analysis. Those values were then converted to 2017 US dollars. Seven of the sixteen studies were excluded from the analysis because the methods underlying their estimates were incompatible with our approach. For example, Armstrong et al. (2012) do not use specific emissions or socio-economic scenarios but combine impacts from studies that use different underlying projections and characterize the "best- and worst-case scenarios." Without specific information on the CO2 emissions and the population and income projections on which the estimates are based, we cannot convert them into comparable units and include them in our analysis.

All studies included in our analysis provide multiple estimates for the same economic sector that differ by emissions scenario, socio-economic projections, geographic area of study, or other modeling assumptions. Estimates from the same study that differ in a material way, such as emissions scenario or biological sensitivity to ocean chemistry, provide meaningful variation to our data and are included. When estimates only differ in modeling assumptions that do not inform our analysis, duplicative estimates are omitted. Narita et al. (2012) is notable for providing 186 estimates for 31 different countries and regions under two different emissions scenarios. Two-thirds of those values, however, only reflect different assumptions regarding income growth compared with the remaining third. We do not consider that a meaningful distinction and include just one third of the values reported corresponding to a single income growth assumption. Most studies provide far fewer estimates which raises the question of how to weight the contributions of each study. Each of our analyses addresses this disparity differently. We perform two types of nonparametric bootstrap simulations, one that weights all estimates equally and one that assigns equal weights to each study. The meta-regressions provide clustered standard errors that account for correlations within studies. The details of all approaches are provided in the Methods section. The sections that immediately follow describe the separate impact sectors and the studies belonging to each.

2.1 Commercial Mollusk Fisheries

The ecological response to ocean acidification that has been studied most is the effect on shell growth and dissolution in mollusks (e.g. Gazeau et al. 2013, Parker et al. 2013, Kroeker et al. 2014). The availability of ecological response data combined with readily available market data for valuation, results in the largest number of economic estimates for this impact sector. Four of the five studies that estimate damages in mollusk fisheries rely on changes in shell growth rates as a proxy for expected changes in harvest and assume the two are proportional. There is no evidence to support this relationship and there are no long-term studies of biomass impacts to provide a better link (Garrard et al. 2013). Fernandes et al. (2017) is the lone exception and instead uses a habitat suitability and population dynamics model to predict changes in harvest. Fernandes et al. (2017) and Mangi et al. (2018) estimate impacts to revenue in mollusk fisheries in the UK through the end of the century. Cooley and Doney (2009) and Moore (2015) estimate impacts to the US mollusk fishery in 2060 and 2100. Cooley and Doney estimate changes in revenue while Moore estimates consumer surplus impacts. Narita and Rehdanz (2017) estimate consumer and producer surplus in Europe under different emissions scenarios. Narita et al. (2012) also provide separate estimates for producer and consumer surplus for 31 different countries and regions.

2.2 Commercial Crustacean Fisheries

Mangi et al. (2018) is the only study used in the meta-analyses that values decreased harvest of crustaceans. The authors use the average of effect sizes across three studies that examine growth and survival among crustaceans and apply that to harvest revenues in the UK through the end of the century.

2.3 Commercial finfish harvest

While there is evidence that some types of finfish can be affected by ocean acidification directly (Dixson et al. 2010, Simpson et al. 2011, Mathis et al. 2015), the studies that value changes in harvest resulting from ocean acidification do so by modeling changes in habitat and prey availability. The Fernandes et al. (2017) analysis is limited to lost revenues from cod and sea bass harvested in the UK. Speers et al. (2016) model the effects of ocean warming and acidification on coral reef area in eight regions and value the consumer surplus losses from a global reduction in harvest of eleven types of fish that rely on coral reefs for habitat. Colt et al. (2016) estimate lower and upper bounds for lost producer rents and consumer surplus worldwide for all marine fisheries.

2.4 Subsistence and Recreational Fishing

Economic impacts of ocean acidification on subsistence fisheries in developed countries is likely to be minimal. In developing countries, Colt et al. (2016) find that most subsistence fishing occurs in inland waters, but they find a notable exception in Vietnam and focus on that country for their analysis. Colt et al. (2016) is also the only study that provides monetary estimates of losses to the recreational fishing sector, though the methods are somewhat simplistic. We combine the estimates of subsistence and recreational fishing into a single sector because they often coincide and dividing them into separable categories would risk double counting losses from the same activity.

2.5 Coral Reef Recreation

Brander et al. (2012) develop a reduced form model of coral reef loss as a function of atmospheric CO2 concentrations and link it to a meta-analytic value function based primarily on recreational travel cost studies. Using various CO2 emissions scenarios and coral reef sensitivities, Brander et al. (2012) provide several estimates of global consumer surplus losses. Colt et al. (2016) assume a total loss of recreation value from coral reefs by the end of the century and transfer two per-hectare values to provide high and low estimates. Perhaps reflecting the error of using average values rather than marginal values, Colt et al. estimate losses orders of magnitude smaller than Brander et al. despite assuming a total loss of the resource.

3. Methods

We perform two types of meta-analysis with the collected data, non-parametric bootstrap and meta-regression. Bootstrapping is a statistical method to characterize the distribution of a set of datapoints by randomly resampling from that set with replacement and calculating summary statistics from each sample. Non-parametric bootstrapping simply draws from the collected data without simulating additional data based on distributional assumptions. The set of data points we draw from are per-capita values using the total impact estimates from the original studies and population projections for the study region that are consistent with the socio-economic scenarios of each study. We also examine per-capita values as a percent of projected income in the corresponding year of analysis to control for income differences across regions.

The studies we include in the meta-analysis use either the Special Report on Emissions Scenarios SRES; IPCC 2000) or the Representative Concentration Pathways (RCP; IPCC 2007) to provide atmospheric CO2 concentrations in the year of analysis. The SRES scenarios were developed with specific population and income growth projections underlying them. The RCP projections only had narrative scenarios describing population and income growth for each[1]. van Vuuren and Carter (2014) provide a mapping of SRES projections to the most comparable RCP scenarios allowing us to calculate per capita impacts and per capita incomes for studies that used RCP scenarios. The mapping between the two sets of projections is as follows: (i) SRES A2 is used for RCP 8.5, (ii) SRES B2 for RCP 6.0, (iii) and SRES B1 for RCP 4.5. The Center for International Earth Science Information Network provides downscaled projections of GDP and population allowing us to calculate per capita impacts and income for any country (Gaffin 2004).

To generate the set of bootstrap estimates for per-capita impacts we perform the following algorithm on each impact sector. We begin by setting the size of the bootstrapped sample equal to the number of estimates available in each sector n_s. We then draw n_s values with replacement from the set of estimates for that sector and take the mean of those draws. Repeating this algorithm 10,000 times will provide a sampling distribution of the mean estimate for each sector from which we can calculate the first and second moments. This approach ignores which study each estimate is drawn from and gives equal weight to each estimate. To assign equal weight to each study, we modify the algorithm by finding the smallest number of estimates provided by a study in each sector n_{si}. We then sample, with replacement, n_{si} values from each study and combine the draws from all studies in a sector to generate one pseudo-dataset. Repeating this algorithm 10,000 times provides a sampling distribution for the mean value in each impact sector that places equal sampling weight on each study.

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[1] Shared Socio-Economic Pathways (SSPs) were later developed to complement the RCP scenarios but were intentionally not developed to represent individual pathways, but rather provide various scenarios for different pairwise matching between the GHG concentrations and socioeconomic projections.

Meta-regression allows us to examine relationships between the economic impact estimates and features of the underlying studies while controlling for other factors. Our primary focus is the relationship between economic impacts and the emissions scenarios used in each study, or more specifically, the atmospheric CO2 concentrations in the year of analysis. Two meta-analyses of climate change impacts provide useful examples for our effort. Tol (2015) and Howard and Sterner (2017) review the literature and analyze global estimates of total economic damages from climate change. While the ocean acidification literature is not mature enough to provide estimates of total damages, the model specifications and econometric approaches the authors use to address the error structure of their data provide helpful insight. Tol (2015) analyzes 21 estimates from 18 studies using four functional forms including polynomial and logarithmic functions of temperature change and atmospheric CO2 concentration in addition to a non-parametric kernel regression. None of the estimated damage functions perform well and monotonic specifications are among the worst, indicating that small increases in temperature result in economic benefits. Howard and Sterner (2017) find that previous meta-analyses that do not address heteroskedasticity and correlation of errors from the same study produce inconsistent and inefficient estimates. To address these shortcomings, they estimate heteroskedastic robust models using one estimate from each study, unless multiple estimates are deemed independent (i.e. produced using different models and data). The specification chosen by Howard and Sterner is more restrictive than Tol's, however, assuming a zero intercept and a quadratic function of temperature change.

Unlike Tol (2015) and Howard and Sterner (2017), we lack estimates of total economic impacts to specify a global damage function. Instead we perform several exploratory meta-regressions in order to provide insight on how features of the original studies influence the economic estimates. We also test several specifications and estimation approaches to examine the impact of each on the results. The primary driver of economic damages that interests us is atmospheric CO2 concentrations. While using an indication of seawater chemistry such as aragonite saturation level or pH is an option, the relationship between these variables is well understood and using CO2 concentrations facilitates direct comparisons with estimates in the climate change literature. The relationship between atmospheric CO2 concentration and seawater chemistry is non-linear with aragonite saturation decreasing at a diminishing rate as CO2 increases (Hall-Spencer and Harvey 2019). We account for this non-linearity by including the square of the change in CO2 concentrations in our model specification. We also control for whether the original study included warming impacts in their model and systematic differences in damage sectors by including sector dummies in one specification and sector dummy-CO2 interaction variables in another.

We take two different approaches to accounting for the error structure of our data. First, it is likely that different estimates from the same study are correlated because they rely on the same data and model and ignoring correlation among observations will underestimate the standard errors. To address the error structure, we estimate a heteroskedastic and cluster-robust variant of the Huber-White "sandwich" estimator of the variance co-variance matrix,

$$\hat{V}_R\left(\hat{\beta}\right)=\left(X'X\right)^{-1}\sum_{g}^{G}X_g'\hat{u}_g\hat{u}_g'X_g\left(X'X\right)^{-1},$$

where *g* indexes the clusters, *X* is the independent variable data matrix, and $\hat{u}$ is the vector of model residuals.

Cameron et al. (2008) point out that a limitation of the cluster-robust standard errors is that the asymptotic justification assumes that the number of clusters goes to infinity. This is not a problem for data with 30 clusters or more, but we are limited to just nine studies which can bias our standard error estimates further. Cameron et al. (2008) develop several approaches that bootstrap at the cluster level to overcome this limitation and we implement the “wild bootstrap” variety in a second estimation approach.

4. Results

The nascent status and cross-disciplinary nature of this area of research present several challenges to conducting a meta-analysis. The first is the paucity of estimates in many of the economic impact categories. Most economic damage sectors have just one or two studies providing estimates. Another challenge is the lack of information provided by each study. Several studies could not be included because they did not provide information necessary to convert the monetary estimates into directly comparable values. Very few studies provide standard errors for the estimates, which are often used in meta-analyses to weight the contribution of each estimate. Despite these limitations, we carry out the most rigorous synthesis of the literature possible and include with our conclusions a set of suggestions that will improve researchers’ ability to conduct meta-analyses in the future.

4.1 Non-Parametric Bootstrap Results

Our non-parametric meta-analysis treats the data as samples from a larger population of values. Within each economic sector we generate a mean value and the standard deviation of that mean. The commercial mollusk and finfish impact sectors provide consumer and producer impacts that can be analyzed separately. The remainder of the sectors provide just one or the other measure. Table 2 provides the bootstrap means and standard deviations of the per capita economic impacts for each sector and for the total across sectors. To generate summary statistics for the totals across sectors, the vectors of bootstrap means for each sector are horizontally summed creating a vector of total damages of the same length. The mean and standard deviation of that vector of total damages are shown in the last row of table 2[2]. Estimates generated with the standard algorithm that gives all estimates equal weight and the modified algorithm that weights studies equally are shown separately.

Table 2 Non-parametric bootstrap analysis of per-capita economic impacts by the year 2100 (impacts reported in 2017 US Dollars)

					Equally Weighted Estimates		Equally Weighted Studies	
Impact Sector	Number of Studies	Number of Estimates Included	Range	Median	Mean	Standard Deviation	Mean	Standard Deviation
Mollusk Consumers	3	39	[0.002, 50.716]	1.466	4.445	1.375	2.485	1.851
Mollusk Producers	5	54	[0.002, 37.170]	1.445	4.077	0.788	2.583	1.211
Crustacean Producers	1	4	[1.051, 9.109]	3.643	4.37	1.513	4.347	1.522
Fish Consumers	2	4	[0.537, 10.441]	3.799	4.597	2.078	4.644	0.652
Fish Producers	2	18	[-10.488, 35.843]	4.027	2.182	2.163	2.99	3.644
Subsistence and Recreational Fishing	1	4	[0.298, 5.171]	1.889	2.318	0.89	2.322	0.886
Coral Recreation	2	6	[-9.433, 118.942]	5.022	35.894	18.768	27.753	16.855
Total	9*	129	-	-	57.88	19.21	47.13	17.48

*Total number of studies is not equal to the column sum because some studies report estimates for multiple sectors

The column containing the number of studies in each sector reveals how thin the literature is in this area, for some sectors in particular. While the range of estimates for most sectors is strictly positive, indicating economic losses, the lower bounds of ranges for fish producers and coral recreation indicate

[2] The mean of the total is mathematically equivalent to the total of the means and this can be confirmed by summing the means of the sectoral impacts. The standard deviations, however, are not and require the additional step of generating a vector of total bootstrap means.

that some studies, under certain sets of assumptions, project economic gains for those sectors by the end of the century. The medians of most sector estimates are lower than the means indicating distributions that are skewed to the right, with a small number of large estimates pulling up the mean values. Fish producer impacts are the single exception with a median that is greater than the bootstrapped mean. Comparing the mean values between bootstrap algorithms that weight either estimates or studies equally, the differences are modest. Equally weighting the studies tends to produce somewhat lower mean estimates in most sectors but overall, the differences are not striking.

Another notable feature of the data is the extremely high per capita value in the coral recreation sector. The upper bound of the range for that sector is more than twice the upper bound of any other sector. It is also worth noting that the negative lower bound and the large upper bound for the coral recreation sector are both taken from the Brander et al. (2012) study. The lower bound estimate is based on the SRES B1 scenario that predicts aggressive climate change mitigation and international cooperation. The scenario also assumes strong per capita income growth so that by the end of the century coral reefs are recovering and demand for recreation is increasing, driving up their value. The upper bound is found using the SRES A1 scenario which assumes only modest mitigation relative to the business as usual scenario but quickly increasing per capita income. The result is large losses of coral reefs coupled with increasing demand for a dwindling supply creating large per capita impacts.

The last row of table 2 contains means and standard deviations for the total damages across sectors. Recall, each sectoral estimate is the per capita economic impact from ocean acidification in the year 2100. Sectors were defined to allow summing across them without double counting, so those figures represent total per capita impacts for the sectors with monetized estimates in the published literature. The skewness of the distribution of the sectoral estimates and the relatively large estimate for the coral reef recreation sector is cause for skepticism. Clearly more research into these impacts is needed and standardizing the valuation approaches and economic concepts used by the authors to generate their estimates would improve our ability to interpret and synthesize the results.

While the statistics provided in table 2 are useful for summarizing the economic impacts by sector, they do not shed light on the distributional impacts of ocean acidification. The dollar values shown above are modest by the standards of developed countries but could be more substantial for people with lower incomes. To address that omission, we perform the analysis again, this time expressing the economic impacts as a percent of projected per capita income in the year and region of study. Table 3 shows the ranges, means, and standard deviations of the results for the equally weighted estimates and equally weighted studies algorithms. The final row contains the means and standard deviations for the summations across sectors.

Table 3 Non-parametric bootstrap analysis of economic impacts expressed as percent of income

		Equally Weighted Estimates		Equally Weighted Studies	
Sector	Range (%)	Mean (%)	Standard Deviation	Mean (%)	Standard Deviation
Mollusk Consumers	[9.646e-07, 4.783e-02]	0.0037	0.0015	0.0021	0.0020
Mollusk Producers	[9.646e-07, 3.505e-02]	0.0038	0.0008	0.0025	0.0012
Crustacean Producers	[5.811e-04, 5.037e-03]	0.0024	0.0008	0.0024	0.0008
Fish Consumers	[2.734e-03, 3.417e-02]	0.0157	0.0065	0.0157	0.0021
Fish Producers	[-9.579e-03, 2.980e-02]	0.0027	0.0022	0.0072	0.0049
Subsistence and Recreational Fishing	[9.763e-04, 1.692e-02]	0.0076	0.0029	0.0076	0.0029
Coral Recreation	[-1.001e-02, 1.643e-01]	0.0599	0.0261	0.0470	0.0224
Total	-	0.096	0.027	0.084	0.023

The values in table 3 are expressed in percentage terms so most sectors have mean impacts on the order of thousandths of a percent of per capita income. Not surprisingly the relative magnitudes among sectors is similar to our results when expressed in dollar terms. Coral reef recreation accounts for the largest damages, as a percent of income, with mean estimates an order a magnitude larger than all but one of the other sectors. The exception is impacts to fish consumers which, along with subsistence and recreational fishing, plays a larger role in total damages when expressed as percent of income rather than dollars (see figure 1). This shift in importance is consistent with the findings of Cooley et al. (2012) that many lower income countries depend on marine resources for protein and are not equipped to adapt to the anticipated impacts of ocean acidification. Total damages sum to less than one-tenth of a percent of per capita income. In comparison, a meta-analysis of climate change impacts performed by Tol (2018) finds an average impact of 1.5 percent of income given a 2.5 degree C increase in temperature which would be consistent with the moderately optimistic climate scenarios such as SRES A1B.

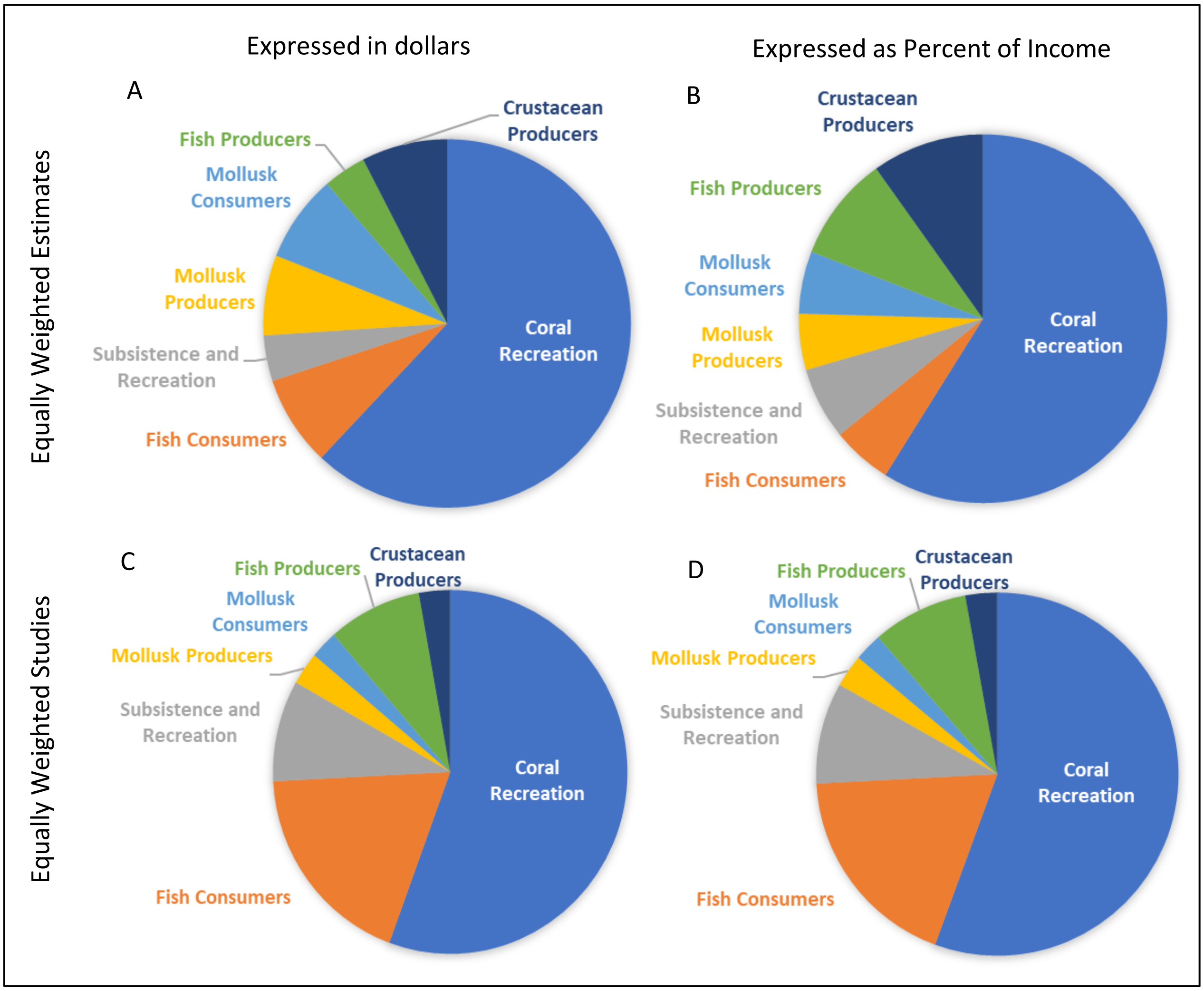

Figure 1 Relative magnitudes of damage sectors under different weighting approaches and value units. Panel A: Impacts in dollar terms, equally weighted estimates; Panel B: Impacts in dollar terms, equally weighted studies; Panel C: Impacts as percent of income, equally weighted estimates; Panel D: Impacts as percent of income, equally weighted studies.

The four panels of figure 1 provide comparisons of our bootstrap results across weighting approaches and units of value. Comparing charts that are horizontally adjacent shows how the shares of total damages change when all included estimates receive equal weight versus when we weight studies equally. Comparing charts vertically shows how the relative magnitudes of damage sectors change when they are expressed in dollar terms versus percent of income. There are many subtle differences but here we discuss the few that we find noteworthy.

First, comparing charts horizontally, we see that giving studies equal weight, rather than estimates, results in a smaller impact to fish producers. Only two studies provide estimates for fish producer impacts: Colt et al. (2016) which provides two estimates and Fernandes et al. (2017) which provides sixteen. There are many differences in how these two studies derive their estimates including methodology and the economic concept used to measure damages (i.e. producer rents versus revenues), so we cannot attribute this shift in relative importance to any single factor. Comparing charts vertically, mollusk and crustacean impacts have a larger influence when expressed in dollar terms and that influence is replaced by fish consumers and recreational and subsistence fishing when expressed as a percent of income. Again, there are too many differences between the studies in these sectors to attribute this difference to any specific features of the underlying studies. We only perform these comparisons to show how different, but perfectly valid, interpretations of the literature can lead to very different conclusions. Finally, the primary motivation for weighting studies equally, rather than estimates was the Narita et al. (2012) study that provides 62 of the 93 estimates for the mollusk producer and consumer sectors. However, comparing the left-hand side charts with those on the right does not reveal a large change in the influence of mollusk impacts on total damages when the Narita et al. estimates are down weighted.

4.2 Exploratory Meta-Regressions

We will present results from a total of six different models: three model specifications each estimated using two approaches for calculating p-values. To address the issue of outliers, we drop observations with per capita loss estimates greater than $50 which is roughly equal to three standard deviations from the mean estimate. This results in three estimates being removed from the model: two estimates of global coral reef recreation losses from Brander et al. (2012) of $72 and $119 and one estimate from Narita et al. (2012) of $51 for producer impacts in China’s mollusk sector.

The most parsimonious specification (Model 1) regresses per capita economic impacts on a linear combination of per capita income, CO2 concentration, CO2 concentration squared, and an indicator variable for whether warming was explicitly included in the model producing economic impacts. The purpose of this specification is to test for expected relationships between the emissions scenarios and economic impacts while controlling for the size of the affected population and their projected income under the corresponding scenarios. Table 4 presents the results of Model 1 in the second column. Since coefficient estimates are consistent under both estimation approaches, only the p-values will vary. The algorithm to perform wild bootstrap estimation does not generate standard errors but does generate p-values (Cameron et al. 2008). Roodman et al. (2019) argues against backing standard errors out of these results because such an exercise would be based on asymptotic theory and assumes a large number of clusters. To present results that are comparable across estimation approaches we present only p-values.

Table 4 Meta-Regression Results

Independent Variable: Per-capita economic loss	Model 1	Model 2	Model 3
Dependent Variable	**Coefficient Estimate** (Cluster Robust p-value) (Wild Bootstrap p-value)	**Coefficient Estimate** (Cluster Robust p-value) (Wild Bootstrap p-value)	**Coefficient Estimate** (Cluster Robust p-value) (Wild Bootstrap p-value)
per capita income ($100,000)	**0.50791** (0.014) (0.000)	**0.48660** (0.001) (0.000)	**0.55146** (0.001) (0.000)
CO2 change (ppm)	**0.06168** (0.069) (0.088)	**0.06123** (0.177) (0.206)	**0.06345** (0.153) (0.270)
CO2 change squared (ppm^2)	**-0.00006** (0.166) (0.144)	**-0.00006** (0.399) (0.384)	**-0.00007** (0.246) (0.270)

warming	**5.37615** (0.016) (0.000)	**7.00234** (0.027) (0.000)	**5.87688** (0.034) (0.000)
mollusk		**2.10432** (0.335) (0.520)	
crustacean		**1.40855** (0.231) (0.430)	
finfish		**-1.02055** (0.696) (0.782)	
coral recreation		**5.87250** (0.219) (0.492)	
CO2 x mollusk			**0.00266** (0.535) (0.536)
CO2 x crustacean			**0.00194** (0.307) (0.406)
CO2 x finfish			**0.00193** (0.637) (0.764)
CO2 x coral recreation			**0.01406** (0.377) (0.482)
constant	**-11.44769** (0.046) (0.004)	**-13.6747** (0.047) (0.002)	**-12.44318** (0.085) (0.062)

The results of Model 1 confirm our priors regarding the effects of income, CO2 concentrations, and inclusion of warming impacts on per-capita economic impacts. First, we would expect per-capita economic losses to be greater in countries and regions with higher incomes. According to the results of Model 1, for every $100,000 in per-capita income annual economic losses tend to increase by $0.50. The cluster-robust p-value indicates that this result is significant above the 95% level using a two-tailed test and that improves under the wild bootstrap model to greater than 99.9%. Likewise, as atmospheric concentrations increase there is a corresponding increase in economic losses that is significant at the 90% level for the cluster-robust and wild-bootstrap models. The squared term is negative indicating economic losses increase with CO2 concentrations at a decreasing rate. While this effect is not significant at traditional confidence levels, it is consistent with the non-linear relationship between CO2 concentrations and uptake of CO2 by the ocean as temperatures increase. Finally, we see that including warming when modeling the economic impacts of ocean acidification increases annual per-capita losses by more than five dollars, on average. This finding is also highly significant in both models. All models have statistically significant constant terms that are somewhat large and negative. This is likely due to the eight observations that predict positive economic impacts under the more moderate emissions scenarios.

Models 2 and 3 take different approaches to controlling for the damage sector for which the economic impacts are estimated, though neither finds statistically significant differences for any of the sectors relative to the omitted category of subsistence and recreational fishing[3]. Model 2 includes indicator dummy variables for impact sectors allowing intercept shifts of the regression function. Model 3 instead includes sector-dummy interaction variables with change in CO2 concentrations. This allows the slope of the function in the CO2 dimension to differ among sectors. The sign and magnitude of the coefficients on the variables shared with Model 1 are consistent across all models, though the CO2 is no longer statistically significant at the 90% level. This is a likely indication of some partial multicollinearity

[3] Removing the two Brander (2012) outlier observations from the data affects the results. Including those observations results in rather large and statistically significant effects for the coral recreation sector.

between the sector dummies and the emissions scenario. In other words, some sectors tend to examine more extreme scenarios while other sectors are modeled under moderate ones. Such inadvertent correlation would result in the CO2 variables losing statistical significance as we control for differences among sectors.

5. Conclusion

This paper is the first to review and synthesize all published studies of the economic impacts of ocean acidification. Doing so not only required searching the literature and identifying relevant studies but also converting the disparate estimates into comparable values using emissions and socioeconomic forecasts corresponding to each study. To generate an aggregated measure of impacts from these diverse estimates we developed a set of seven additively separable economic impact sectors that allow us to characterize the distribution of estimates within each sector and sum across them.

Our search of the literature yielded 18 studies of the economic impacts of ocean acidification but only nine were conducted in a way that permitted inclusion in our analysis. Those studies provided 129 estimates that we deemed independent enough to enter the analysis as individual data points. We found there was far more coverage of impacts to mollusk markets than any other sector, a total of 93 independent estimates from 6 studies. Sixty-two of those estimates were supplied by a single study, however, while the median number of estimates provided by all studies was six.

We took two different meta-analytic approaches to examine the literature. We performed non-parametric bootstrap which allowed us to characterize the distribution of estimates within each sector and the aggregated impacts without assuming anything about an underlying distribution. We performed two types of bootstrap algorithms, a naïve approach that gives all estimates equal weight and another that weights each study equally. Mean impacts tend to be lower when studies receive equal weight and, with the exception of coral reef recreation, all sectors had annual per capita losses between two and five dollars. The mean annual per capita loss of $36 in the coral recreation sector is driven by the Brander et al. (2012) study which reports estimates ranging from -$9 (economic benefits) to $119. Summing across sectors we find that total per capita losses have a mean value of $58 when all estimates receive equal weight and $47 when studies are weighted equally. Using forecasts of per capita income that are consistent with the emissions scenarios used to generate the original estimates we find that total economic losses average less than 0.01 percent of income.

The meta-regression models allow us to examine how the emissions and socioeconomic scenarios affect the estimates and whether the estimates tend to be consistent with our expectations based on ocean chemistry and economic theory. Regression results are largely consistent with our prior expectations. As real income increases, demand for goods impacted by ocean acidification is expected to increase and magnify economic losses. The results of our cross-sectional analysis of losses across countries with different projected per capita incomes are consistent with that principal. The biophysical impacts of ocean acidification will become more pronounced as emissions increase and our regression results show that the corresponding economic losses are also positively correlated with emissions. We find weak evidence that losses increase with emissions at a diminishing rate but that finding is not significant at traditional confidence levels. Another expectation that is supported by our results is that when warming impacts are included in the modeling of biophysical impacts the predicted economic losses tend to be greater.

Reviewing the breadth of the literature on the economic impacts of climate change, very few studies focus on ocean acidification. Further, the ones that do tend to focus on mollusk markets, leaving large gaps in our understanding of what the total economic impacts could be. We encourage studies of economic impacts to other ecosystem services, particularly those provided by coral reefs. There is a robust literature on the biophysical impacts of acidification and warming and coral reefs provide a variety of ecosystem services that have been valued by resource economists (e.g. Pascal et al. 2016, Laurans et al. 2013). As this literature develops, we recommend authors use specific emissions and socioeconomic scenarios when modeling economic impacts. Being able to link monetary damage estimates to time paths of greenhouse gas emissions and forecasts of population and income growth is critical for specifying economic damage functions. Finally, we encourage more resource economists to take up this research question which will not only help to fill the gaps in the literature but also improve the quality and consistency of economic models used to forecast economic losses from ocean acidification.

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