Appendix: Economic Effects of an Ocean Acidification Catastrophe

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1. OA scenario details

Our OA scenario is based on IPCC RCP 8.5 and its extension to 2300, ECP 8.5 (Riahi et al. 2011). CO2 concentrations reach 1,000 ppm shortly after 2100 and stabilize at about 2,000 ppm shortly after 2200. Ocean average pH levels decline by about 0.3 to about 7.8 in 2100. RCP 8.5 does not include pH and ocean chemistry beyond 2100, so we verified that the RCP 8.5 CO2 concentrations are consistent with those from previous high-emission scenarios (such as SRES A1F1 and A2) and also with the parameters of widely-used projections of ocean conditions in 2200 and beyond. We have loosely adopted Caldeira and Wickett's (2005) "5,000 Pg C" case, under which pH falls to about 7.5 in 2200. This projection is quite similar to RCP 8.5 in that atmospheric CO2 concentrations reach 1,000 and 2,000 ppm in about 100 and 200 years. (5,000 refers to cumulative total C emissions in petagrams (1 Pg = 1 Gigatonne); under RCP 8.5 cumulative emissions exceed this level in about 2200).

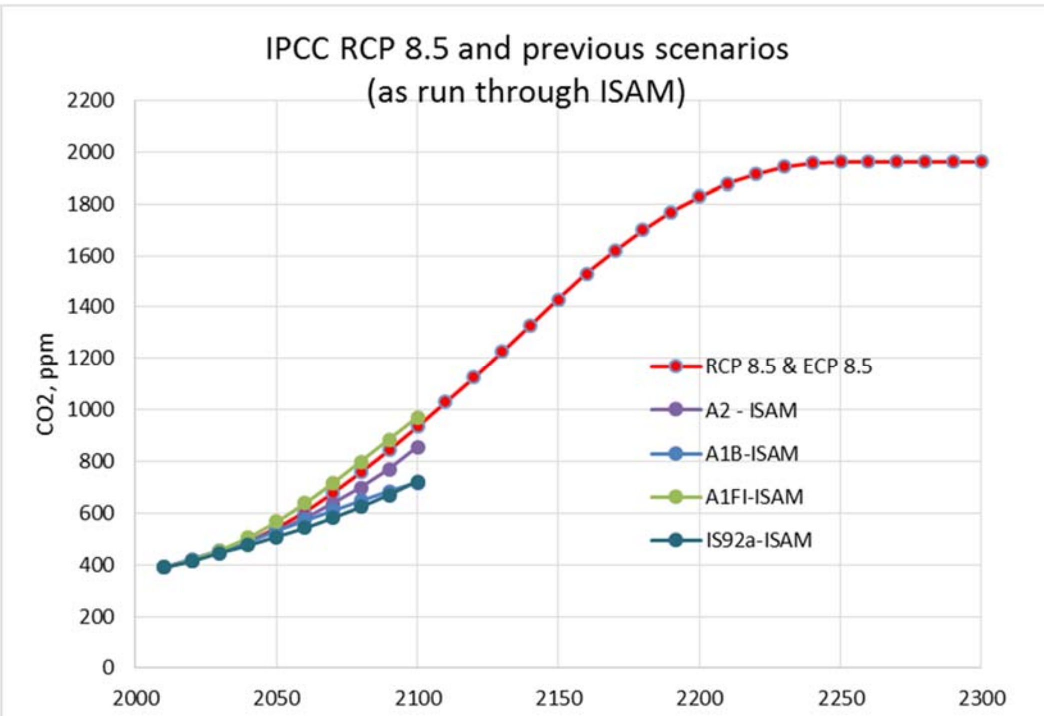


Figure A-1. CO2 concentrations under RCP 8.5 and predecessors

source for predecessor scenarios: http://www.grida.no/climate/ipcc_tar/wg1/531.htm

The reason for tying together RCP 8.5 and previous scenarios is that most recent natural science work was done based on Caldeira and Wickett and/or SRES scenarios; as a practical matter that meant subjecting organisms to CO2 concentrations of 1,000 and 2,000 µatm. Studies prior to about 2005 were apparently criticized for using much higher concentrations.

2. Further discussion of capture fisheries and aquaculture

Producer rents from Alaska salmon fisheries

The Alasks salmon fishery provides direct data on the market value of producer rents from a fishery that is managed to limit, to some extent, the amount of effort. We analyzed these data to derive one estimate of rents as a percent of ex-vessel fish value.

Limited entry permit prices and ex-vessel values for the Alaska salmon fishery were calculated from the Alaska Commercial Fisheries Entry Commission's "Participation and Earnings" reports (https://www.cfec.state.ak.us/fishery_statistics/earnings.htm). The CFEC refers to ex-vessel values as "earnings" in describing the data.

We analyzed data on the reported sales price of limited entry salmon permits and compared it to the ex-vessel value of the catch. The data cover traded permits from among more than 11,000 outstanding permits held during the years 1985-2014. Total ex-vessel value is reported directly. We calculated estimated total market value as (number of permits held) x (average permit price). The ratio of total permit market value to total annual ex-vessel value is 1.0 averaged over the past 30 years and currently equals about 1.2.

The market value of permits – about $750 million – can be used in two ways. First, it serves on its own as a direct measure of the present vale of all future expected rents to producers from a world-class capture fishery. Second, the ratio of 1.0 – 1.2 can be applied to reported data on the ex-vessel value other capture fisheries. Using a discount rate of 5% suggests that annual rents from reasonably well-managed capture fisheries are approximately 5 to 6% of annual ex-vessel values. Applying 6% to total world ex-vessel value in 2012 ($115 billion per ftp://ftp.fao.org/FI/STAT/summary/appIIybc.pdf x marine capture fraction 0.87) yields $6 billion dollars per year in 2014 dollars as an estimate of global rents from marine capture fisheries.

Table A-1. Market value of permits compared to ex-vessel value for the Alaska salmon fishery (millions of 2014 dollars)

	historical avg 1985-2014	current value (avg 2012-2014)
annual ex-vessel value	618.8	619.9
market value of permits	618.3	758.5
ratio of permit market value to ex-vessel value	1.0	1.2
number of permits held	11,583	10,931

Permit values track current-year ex-vessel values quite closely. Figure A-2 shows this correspondence for the Bristol Bay drift gillnet fishery, which is by far the largest (by value).

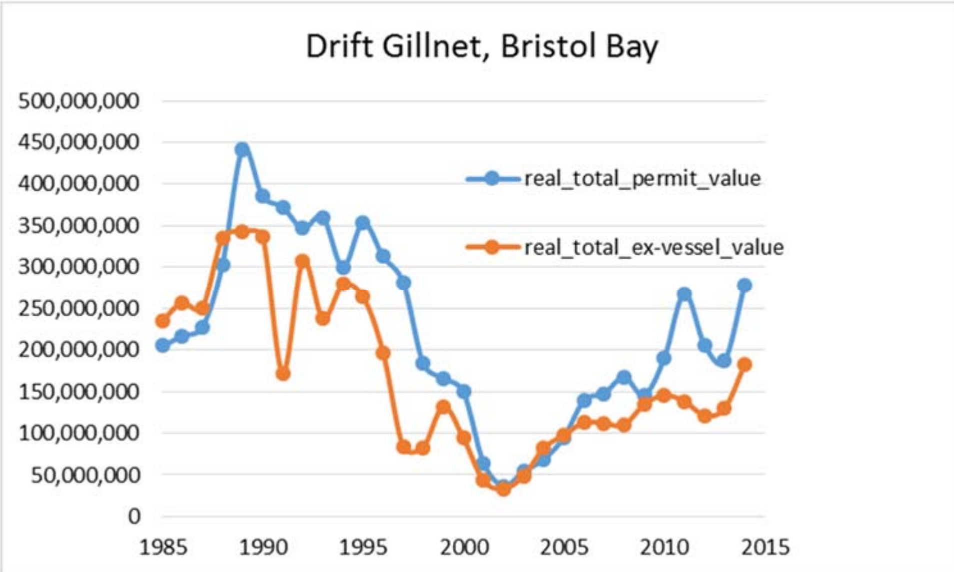


Figure A-2. Limited entry permit values and ex-vessel catch values for the Bristol Bay, Alaska salmon fishery

source: author calculations from Alaska Commercial Fisheries Entry Commission data.

Potential producer rents estimated by World Bank

The World Bank (2015) currently estimates that global capture fisheries have a current (circa 2012) capitalized value of *potential* rents, assuming continued progress toward an efficient level of fishing effort and fish stocks, ranging from $942 billion to $1,451 billion, using a discount rate of 5% (World Bank 2015). Their estimated potential range of annual rents is therefore $47 – 73 billion per year in 2012 dollars, or $49 – 75 billion in 2014 dollars.

Aquaculture

Tables A-2 and A-3provide context for assessing the importance of marine aquaculture relative to marine capture fisheries.

Table A-2. World Marine Fish and Shellfish Production , 2013

	Volume (million metric tons)			Share of total		
	Capture	Aquaculture	Total	Capture	Aquaculture	Total
Pelagic Marine Fish	35.1	0.4	35.4	44%	1%	34%
Demersal Marine Fish	20.1	1.1	21.2	25%	4%	20%
Molluscs excl. Cephalopods	2.5	15.2	17.8	3%	61%	17%
Other Marine Fish	11.0	0.6	11.6	14%	2%	11%
Crustaceans	6.0	4.1	10.1	7%	16%	10%
Freshwater and Diadromous Fish	1.6	3.7	5.3	2%	15%	5%
Cephalopods	4.0	0.0	4.0	5%	0%	4%
Total, fish and shellfish	80.4	25.1	105.5	100%	100%	100%

Source: FAO FishStatJ database. Excludes freshwater fisheries and aquaculture. Excludes aquatic mammals, other aquatic animals, and aquatic plants.

Table A-3. World Marine Fish and Shellfish Aquaculture Production Value, 2011-2013

Country (Country)	Species (FAOSTAT group of commodities)	Aquaculture area (Inland/Marine areas)	Environment (Environment)	Unit	2011	2012	2013
All	Crustaceans	Marine areas	Brackishwater	USD 3	14,604,352	14,908,195	18,209,031
All	Demersal Marine Fish	Marine areas	Brackishwater	USD 3	544,134	607,889	589,738
All	Freshwater and Diadromous Fi	Marine areas	Brackishwater	USD 3	1,688,739	1,785,734	1,949,567
All	Marine Fish NEI	Marine areas	Brackishwater	USD 3	447,514	677,063	732,144
All	Molluscs excl. Cephalopods	Marine areas	Brackishwater	USD 3	303,522	297,283	319,016
All	Pelagic Marine Fish	Marine areas	Brackishwater	USD 3	5,799	6,892	8,110
All	Cephalopods	Marine areas	Marine	USD 3	23	25	10
All	Crustaceans	Marine areas	Marine	USD 3	2,246,420	2,326,131	2,312,083
All	Demersal Marine Fish	Marine areas	Marine	USD 3	4,518,981	4,567,557	4,728,551
All	Freshwater and Diadromous Fi	Marine areas	Marine	USD 3	12,938,115	12,991,128	15,249,650
All	Marine Fish NEI	Marine areas	Marine	USD 3	1,056,784	743,562	821,269
All	Molluscs excl. Cephalopods	Marine areas	Marine	USD 3	15,083,475	15,061,722	17,296,792
All	Others	Marine areas	Marine	USD 3	231,603	213,666	208,458
All	Pelagic Marine Fish	Marine areas	Marine	USD 3	2,202,225	2,423,823	2,149,495
Totals					55,871,686	56,610,670	64,573,914
Total, $ billion					56	57	65

Source: FAO FishStatJ database. Excludes freshwater fisheries and aquaculture. Excludes aquatic mammals, other aquatic animals, and aquatic plants.

The following two figures reproduced from the FAO's "State of World Fisheries and Aquaculture 2014" demonstrate that capture fisheries volumes are constant or declining, while aquaculture is a young and rapidly growing industry. The second figure shows that marine aquaculture accounts for about 1/3 of total aquaculture production.

Figure 1

World capture fisheries and aquaculture production

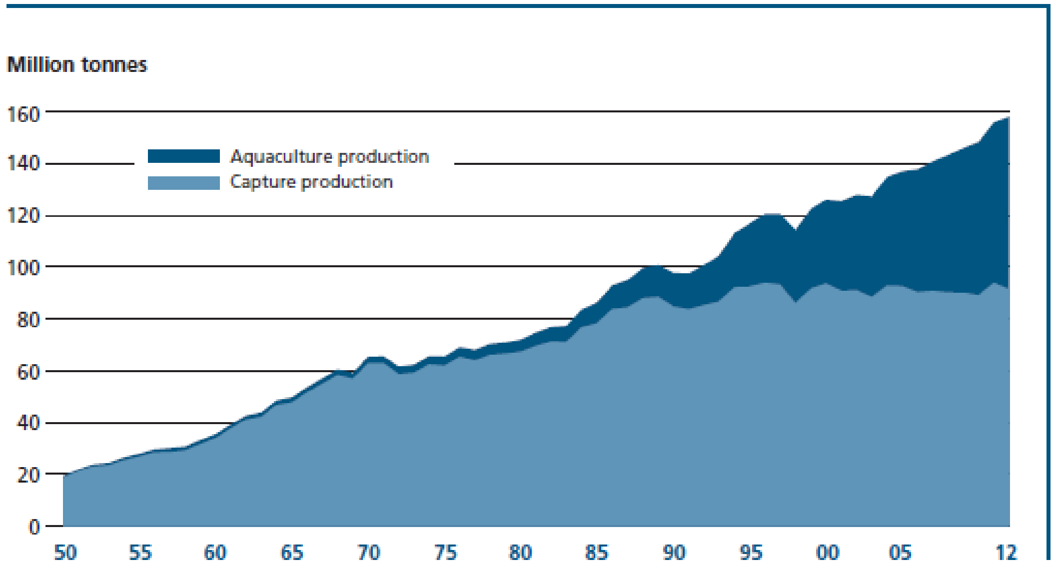
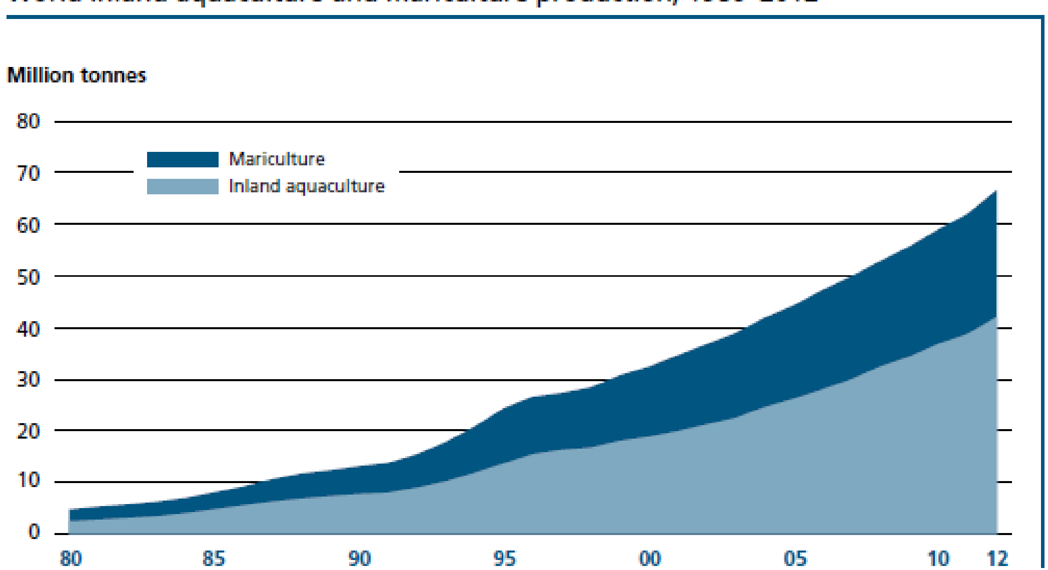


Figure 6

World inland aquaculture and mariculture production, 1980–2012



source: FAO 2015. (http://www.fao.org/fishery/sofia/en)

Consumer surplus from recreational fishing

Although there are scores if not hundreds of studies measuring the consumer surplus from recreational fishing (see Boyle et al. 1998 for one tabulation), and several that focus on saltwater (e.g., Lew and Larson 2012), very few studies report data or results for both expenditures and consumer surplus. These two numbers are needed from the same study in order to generate internally consistent estimates of the ratio of CS to expenditures. We found three studies that, taken together, generate a wide range of estimates for the ratio of CS to ecpenditures. All three used the travel cost method to estimate CS.

Mckean and Taylor (2000) measured total expenditures of $162.8 million and CS of $22.9 million for fishing in the Snake River Basin of Idaho. The ratio of CS to expenditures is 0.14. We do not use this estimate because it is based on fresh water fishing.

Haley et al. (1999) estimated that the ratio of consumer surplus to reported expenditures was about 0.35, based on a survey of more than 5,000 anglers fishing in Alaska. We use this value to generate our "low" estimate.

Kirkley and Kerstetter (1997) measured total expenditures of $303.5 million by Virgina anglers for 2.6 million trips taken in 1994. In a companion study Kirkley et al. (1999) estimated a total consumer surplus of $353.3 million from 2.8 million trips taken in 1996. It is worth noting that the expenditures figure in the denominator appropriately includes spending on boats by boat owners. We adjusted the expenditures to 1994 expenditures for inflation and growth in trips. The resulting ratio is 353.3/346.0 = 1.0. This ratio generates our "high" estimate.

Value of subsistence fish

Our estimates are based on the replacement cost of the fish. (See Duffield 1997 for a discussion of other methods for valuing lost subsistence harvesting opportunities.) The low estimate is the year 2012 capture fisheries world average ex-vessel value per kg:

91.3 million kg / 114.763 $ billion = $1.257 / kg ~= $1.25/kg

The high estimate is based on Alaska subsistence harvest data developed for the *Exxon Valdez* civil trial on Native susbistence losses. The Plaintiffs' higher estimate was $14.01 per pound in 1994 dollars (Duffield 1997, Table 4). Adjusting for inflation using the U.S. CPI-U and converting to kilograms yields $10.1513 per kg. We adopt the value $10.00/kg as a high estimate of the replacement cost.

3. Further discussion of coral reefs

With some exceptions, the valuation literature on coral reefs lacks spatial specificity. This is a general problem with ecosystem service value estimates for coastal and marine areas (Raheem et al. 2012). De Groot et al. (2012) present values per hectare and Costanza et al. (2014) apply them to the estimated 28 million hectares of reef. However, their very large per-hectare value for erosion prevention -- $153,214 -- is based on only two studies, and is the average of the two values: $1.33 and $306,427 (Supporting Info to Costanza et al. 2014).[1] This and similar concerns are further elaborated by Pendleton et al. (2016).

Coral reef recreation values have been studied by more authors, but they, too, exhibit great variation, as shown in Figure A-3, which displays the 29 values used by Costanza et al. (2014). The mean value was $96,302 per hectare.

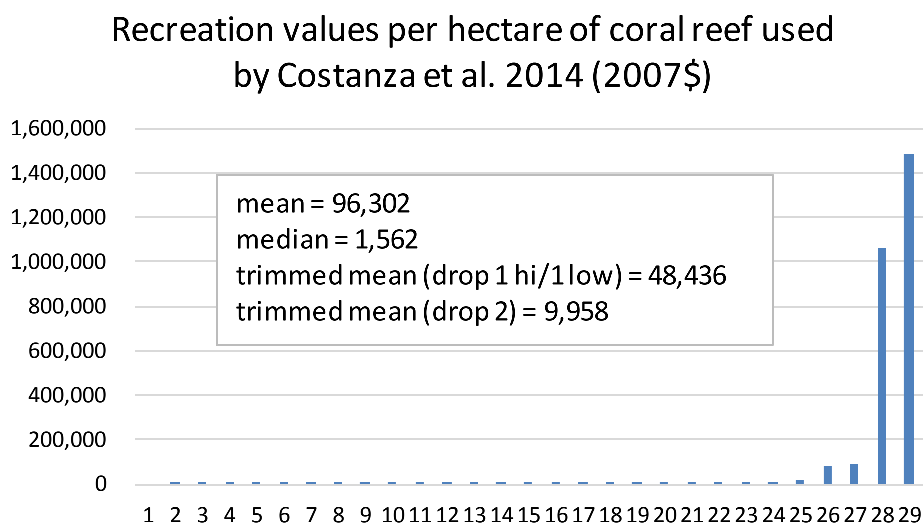


Figure A-3. Recreation values used by Costanza et al.

source: Costanza et al. 2014 – supporting information

Two of the highest values -- $79,000 and $94,000 -- were generated by Burke (2008), but there are several potential adjustments that should be made to these numbers. First, this study used estimated "operating" costs in determining tourism business profits. It is not clear whetehr or how capital costs were treated. Second, 25 percent (St. Lucia) and 40 percent (Tobago) of estimated profits from accomodations and "miscellaneous visitor expenses" were attributed to ecosystem service value, as well as 100% of diving and snorkeling profits. Third, large amounts of service value are associated with local residents' use of beaches, and estimated as foregone

[1] http://www.sciencedirect.com/science/article/pii/S2212041612000101#appd002

wages – meaning that about $5 per hour of resident beach time was assigned as an ecosystem service value of coral reefs.

The authors of this study did an excellent job documenting their assumptions and showing how they affect total valuation numbers. Nonetheless, it is not clear that such high numbers are warranted. We performed the pro-forma adjustments shown in the following table to explore the effects of removing local use benefits and reported accomodations profits. This exercise suggests that a more realistic estimate of coral reef service value could be only 5% of the reported total that was presumably used to develop the deGroot and Costanza numbers. Applying a 0.05 adjustment factor would yield a per hectare value of $4,712 in 2007 dollars. This value is quite close to the mean value of the 4 travel cost studies ($3,834) and to the mean of the 5 contingent valuation studies ($3,738).

Table A-4. Pro forma adjustment of St. Lucia coral reef service values reported by Burke at al. 2008

	$million	%
Reported:		
Accommodation	64.7	37%
Reef Recreation – Diving	4.9	3%
Reef Recreation – Snorkeling and glass-bottom boats	0.8	0%
Marine Park Revenues	0.1	0%
Miscellaneous Visitor Expenses	21.2	12%
Total profits ("Direct Impact")	91.6	53%
Consumer Surplus	2.3	1%
Local use of beaches (foregone wage method)	80.5	46%
Total direct + CS + PS + Local use	174.4	100%
Adjustment: remove accom, misc, local use:		
Subtotal: diving, snorkeling, park fee (CS+PS)	8.1	
ratio of subtotal to total	5%	

After conducting this brief analysis, we chose to use the median value per hectare of $1,562 (year 2007 PPP$) because it is highly unlikely that all 28 million hectares would be developed or exploited for recreation with the same intensity as the sites such as St. Lucia that have, so far, been chosen for economic valuation.

4. Documentation of Future World GDP Projections

Projected GDP in 2100 is from the OECD SSP3 and SSP5 projections (Dellink et al. 2015) developed for the IPCC Shared Socioeconomic Pathways effort (O'Neill et al. 2014). The data were obtained from the SSP database:
https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=series (accessed January 9, 2016).

We adjusted the data from 2005 PPP$ to 2014 PPP$ using the World Bank's data on GDP in current PPP$ and GDP in constant 2011 PPP$.
(http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators. Data series NY.GDP.MKTP.PP.CD and NY.GDP.MKTP.PP.KD).

The final projected amounts for year 2100 are shown in Table A-5.

Table A-5. Projected year 2100 world GDP from OECD projections following SSP3 and SSP5 story lines

Model	Scenario	units	2014	2100	avg growth rate
OECD Env-Growth	SSP3_v9_130325	billion US$2014PPP	108,596	335,315	1.3%
OECD Env-Growth	SSP5_v9_130325	billion US$2014PPP	108,596	1,225,185	2.9%

5. Complete list of references used and literature consulted

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