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The Economic Impact of Ocean Acidification on Coral Reefs

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Abstract: Because ocean acidification has only recently been recognised as a problem caused by climate change, impact studies are still rare and estimates of the economic impact are absent. This paper estimates the economic impact of ocean acidification on coral reefs which are generally considered to be economically as well as ecologically important ecosystems. First, we conduct an impact assessment in which atmospheric concentration of CO2 is linked to ocean acidity causing coral reef area loss. Next, a meta-analysis is applied to determine the economic value of coral reefs around the world. Finally, these two analyses are combined to estimate the economic impact of ocean acidification on coral reefs for the four IPCC marker scenarios. We find that the annual economic impact rapidly escalates over time, because the scenarios have rapid economic growth in the relevant countries and coral reefs are a luxury good. Nonetheless, the annual value in 2100 in still only a fraction of total income, one order of magnitude smaller than the previously estimated impact of climate change. Although the estimated impact is uncertain, the estimated confidence interval spans one order of magnitude only. Future research should seek to extend the estimates presented here to other impacts of ocean acidification and investigate the implications of our findings for climate policy.

Key words: Ocean acidification, coral reefs, economic value

JEL Classification: Q51, Q54, Q57

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1. Introduction

Human activity is increasing the concentration of carbon dioxide in the atmosphere and in the ocean. In the atmosphere, carbon dioxide is a greenhouse gas causing climate change. In the ocean, carbon dioxide is an acid causing ecosystem change. While research on aspects of climate change has generated an enormous number of studies over the last few years, ocean acidification has only recently been recognised as a problem. Impact studies are still rare and estimates of the economic impact are absent. This study estimates the economic impact of ocean acidification on coral reefs which are generally considered to be economically as well as ecologically important ecosystems.

Ocean acidification has a range of impacts on biological systems. It will change the competition between marine plankton species in favour of those that rely less on calcium (Orr et al. 2005;Riebesell et al. 2000), it will negatively affect shellfish (Gazeau et al. 2007;Spicer et al. 2007), it will impact on fish (Ishimatsu et al. 2004), it may benefit highly invasive non-native algal species (Hall-Spencer et al. 2008), and it will reduce coral calcification (Hoegh-Goldberg et al. 2007). However, while the initial impact of ocean acidification is relatively clear, the eventual impact depends on the complex interaction of many species. The estimation of resulting changes in economic values, which generally derive from the higher trophic levels (e.g., top predator fish, marine mammals, sea birds), is therefore also pervaded by uncertainty. Coral reefs are an exception in that the impact of ocean acidification is relatively well understood and they have a range of direct and indirect use values for humans (e.g., coastal protection, fisheries, recreation, amenity). It is for these reasons that this paper is limited to assessing the economic impact of ocean acidification on coral reefs.

There are a large number of economic studies that assess the values of ecosystem services provided by coral reefs. A few of these studies specifically address the impact of climate change on the economic value of coral reefs. Most of these address specific regions such as Australia (Hoegh-Goldberg & Hoegh-Goldberg 2004), Indian Ocean (Westmacott et al. 2002;Wilkinson et al. 1999), Pacific Ocean (World Bank 2000); the Caribbean(Burke & Maidens 2004;Vergara et al. 2009) and the United States (Gibson et al. 2008). Only (Cesar et al. 2003) estimates the global damage of climate change on coral reefs but does not specifically address the impact of ocean acidification. To our knowledge, this is the first study to investigate the economic impact of ocean acidification on coral reefs worldwide.

The current paper is a first step towards filling an important gap in the literature on the valuation of the impact of climate change. The research tract on the economic impact of climate change, started by (Nordhaus 1991), is still incomplete and lacks estimates of both negative and positive impacts (Tol 2008b). Ocean acidification, however, is more than just one of the unquantified impacts. For several reasons, the absence of this climate change impact also has serious implications for the type of policy interventions required. First, since ocean acidification is exclusively driven by carbon dioxide, as opposed to climate change which is also caused by other greenhouse gases, the additional cost associated with carbon dioxide emissions due to ocean acidification changes the trade-offs between the reduction of greenhouse gases (Schmalensee 1993). Second, the absorption of carbon dioxide by the oceans and thus the impact of ocean acidification occur over a short time scale, whereas the warming of the atmosphere substantially lags behind the build-up of greenhouse gases in the atmosphere. This changes the dynamics of optimal emission control, and makes the discount rate less important (d'Arge et al. 1982). Third, the consideration of ocean acidification also has implications for the instrument choice for the potential solution to climate change. Climate change may be countered by geoengineering (Schelling 1996), but ocean acidification would continue unabated and may even accelerate if sulphur particles are used to cool the planet. Therefore, valuing ocean acidification will not only increase the estimates of the Pigouvian tax required to achieve efficient greenhouse gas emissions abatement (Tol 2005), but it will affect other trade-offs and policies too.

The paper proceeds as follows. Section 2 reviews the literature on ocean acidification and its impact of coral reefs, and constructs a simple model. Section 3 presents a meta-analysis of the economic value of coral reefs. Section 4 combines the two to produce a scenario and sensitivity analysis of the economic impact of ocean acidification on coral reefs. Section 5 concludes.

2. Ocean acidification and its impact on coral reefs

(Caldeira & Wickett 2005) show the results of 15 experiments with an ocean chemistry model to predict chemistry changes from carbon dioxide emissions to the atmosphere and the ocean. Although there are a number of mechanisms that lead to increased ocean acidity, the main mechanism is the higher concentration of dissolved CO_2 (Cao et al. 2007;McNeil & Matear 2006;McNeil & Matear 2007;Morse et al. 2006;Ridgwell et al. 2007). This allows us to approximate ocean acidity as a simple function of the atmospheric concentration of CO_2:

(1) $A_t = \alpha\left(M_t - 280\right)^{\beta}$

where A is change in ocean acidity relative to pre-industrial times (in pH) at time t, M is atmospheric carbon dioxide in parts per million by volume (ppmv). The pre-industrial level of carbon dioxide is the assumed value of 280 ppmv. The parameters α = 5.69 (0.04) 10^{-3} and β = 0.67 (0.53-0.86) are based on OLS regression using the results of (Caldeira & Wickett 2005). Figure 1 shows that Equation (1) is a rather good approximation; the R^2 is 99.9%.

A number of studies has estimated the impact of ocean acidification on coral reefs (Andersson et al. 2003;Andersson et al. 2007;Gattuso et al. 1998;Kleypas et al. 1999;Langdon et al. 2000). Table 1 summarizes their results, expressed as a loss in reef area. We assume that reef area is a logistic function in ocean acidity:

(2) $R_t = \dfrac{\gamma A_t}{1 + \gamma A_t}$

Where R is the change in reef area since pre-industrial times, and γ = 0.56 (0.39) is a parameter; its value is the average of the parameters in Table 1. Figure 2 gives reef area as a function of the atmospheric concentration of carbon dioxide, using Equation (1) to compute ocean acidity. The uncertainty shown is the uncertainty about the coral reef response to acidification only; this uncertainty is substantial. At around 1200 ppm, there is a 16.5% chance that coral reefs are extinct.

3. The value of coral reefs

Coral reefs are highly productive ecosystems that provide a variety of valuable goods and services to humans. These goods and services include coral mining and recreational opportunities for diving, snorkelling and viewing (direct use values); amenity services reflected in real estate prices, coastal protection and habitat and nursery functions for commercial and recreational fisheries (indirect use values); and the welfare associated with the existence of diverse natural ecosystems (preservation values). The open-access nature and public good characteristics of coral reefs often result in reefs being undervalued in decision making related to their use and conservation. In response to this, there is now a substantial literature on the economic values of coral reefs. This section synthesises the results of the coral reef valuation literature through a meta-analysis. The data and analysis here are similar to those in (Brander et al. 2007), but this study includes value estimates for all goods and services while Brander et al. was limited to recreation values.

160 separate coral reef valuation studies were collected from a variety of publication outlets, including journal articles, book chapters, occasional papers, reports, and academic theses. In order to compare value observations, information on a number of key variables is required, including coral reef value, goods and services being valued, number of visitors, area of coral cover, location, year of valuation, and valuation method used. 45 studies yielded sufficient information for a statistical meta-analysis. From these 45 studies we were able to code 81 separate value observations, taking multiple observations from single studies. On average 1.8 observations per study were obtained, with a maximum of 12 observations from a single study. Table A1 has the descriptive statistics.

Regarding the geographic representation of the of the sample, 30 observations are for US coral reefs, 21 from South-East Asia, 9 from East Africa, 8 from Australia and 13 from the Caribbean. The value observations have been estimated using a variety of valuation methods. Around half were obtained using the contingent valuation method, with the remainder derived from the travel cost (11), net factor income (7), production function (6), and gross revenue methods (17).

There is no standard reporting format for valuation results and so value observations are reported in a wide variety of units (e.g. total values, per unit of area, per visitor etc.), for different time periods (e.g. per day, per year, NPV over a given time horizon etc.), and in different currencies and years of value. Therefore, we standardised these values to a common metric, which is $\$/km^2/year$ in 2000 prices. The unit of area refers to the area of coral cover. Values from different years were converted to 2000 prices using GDP deflators from the World Bank World Development Indicators. PPP conversions were made to correct for differences in price levels between countries.

The main methodological approach to explaining observed differences in coral reef values is a meta-regression. Meta-analysis is a statistical method for combining study results that allows the analyst to systematically explore variation estimates across studies. Our meta-analysis of coral reef values involves regressing the standardized coral values on a set of explanatory variables. These explanatory variables include geographic (location dummies), ecological (area of coral cover, biodiversity), socio-economic (GDP per capita, population density, goods and services provided, number of visitors), and methodological variables (valuation method used).

The results of the meta-regression are presented in Table 2. The adjusted R^2 value of 0.60 is reasonably high, and indicates that almost two-thirds of the variation in coral reef value is explained by variation in the explanatory variables. In this log-log model, the coefficients measure the constant proportional or relative change in the dependent variable for a given relative change in the value of the explanatory variable. For example, the coefficient of 0.535 for the dummy variable indicating that the coral reef supports reef tourism means that, ceteris paribus, the value of the coral reef will be 71% (i.e., $e^{0.535} - 1$) higher than the average when this service is provided, as compared to when this service is not present.

Regarding the results on the regional indicators, all else being equal, Caribbean reefs (the omitted dummy) have higher values than reefs in any other region, and Australian reefs are least valuable. As one would expect, income per capita, population density, and the number of visitors all have positive effects on coral reef value. More biodiverse reefs are more valuable, and smaller reefs are more valuable (per square kilometer) than are bigger reefs, again as one would expect. The category 'type of goods and services' provided by coral reefs generate only a few significant coefficients on the dummy variables explaining economic value. Coral reefs that have been valued as providing snorkeling opportunities and coastal protection have lower values than the average, but this is significant only at the 10% level. The results on the dummy variables indicating the type of valuation method used are equally inconclusive. Only the contingent valuation method stands out, albeit at the 10% significance level only, yielding lower than average values.

4. Scenarios and results

In this section we combine the results of the two previous sections to calculate the economic impact of ocean acidification on coral reefs and show results for the four marker scenarios of the IPCC Special Report on Emission Scenarios (Nakicenovic, N. and Swart, R. J. 2001). Although controversial (Castles & Henderson 2003;Pielke, Jr. et al. 2008), the SRES scenarios are the standard in climate change impact analysis. Table A2 shows the scenario characteristics of the affected countries, that is, those with coral reefs.

Figure 3 shows the atmospheric concentration of carbon dioxide according to the four SRES scenarios and a standard (Maier-Reimer & Hasselmann 1987) carbon cycle model as embedded in the integrated assessment model FUND (Tol 2008a). The CO_2 concentration in 2100 shows a wide range, from 570 ppm (and falling) in the B1 scenario to 812 ppm (and accelerating) in A2.

Figure 4 shows the resulting change in ocean pH, following Equation (1); in pre-industrial time, ocean PhD was 8.2 (Key et al. 2004). Again, there is a wide range. The change in pH in

2100 varies from -0.25 (but rising) in B1 to -0.38 (and accelerating) in A2. This pattern follows immediately from the CO_2 concentrations in Figure 3.

Figure 5 shows the percentage loss of coral reef area (since pre-industrial times) due to the increased acidity of the ocean, following Equation (2). In 2000, the total area was some 307,000 km^2, but already 7% was lost due to ocean acidification. The loss in 2100 ranges from 16% or 30,000 km^2 (but falling[1]) in B1 to 27% or 65,000 km^2 (and accelerating) in A2. Again, this pattern follows straightforwardly from the pH values in Figure 4. It should be noted that the estimated loss in coral area is only due to projected ocean acidification and not to other factors that may result in coral degradation (e.g. warming, sea level rise, pollution etc.).

Figure 6 shows the global average value per km^2 of coral reef area. The average is a weighted average, using national coral reef area as weights.[2] Several variables feed into the meta-regression (cf. Section 3). Population density and per capita income are part of the SRES scenarios. We assumed that the growth rates are uniform across the countries in the FUND regions,[3] and used these growth rates to extrapolate the national coral reef value. The number of visitors is also important. We used the number of international arrivals according the Hamburg Tourism Model (Hamilton et al. 2005). See Figure A1. Coral reef area also affects coral reef value. We used the areal change of Figure 5. The meta-analysis is about the *annual* value per area of coral reef. We calculate the net present value by assuming that the annual value is constant; we use a Ramsey rate of discount, with a pure rate of time preference of 3% per year and an income elasticity of marginal utility of one.

All scenarios display a rapid rise in per unit area values. We assumed that the meta-regression results are representative for 2000. The average value then was $177 thousand per square kilometre, with a range of $39 to $804 thousand per km^2. This value rises by a factor 67 in the A2 scenario, and a factor 681 in the A1 scenario. Four developments contribute to this. Firstly, population grows substantially. Secondly, coral reef area falls substantially. These two factors contribute relatively little, because the elasticities are relatively small (around 0.5) and because the levels change only moderately. The third development is more important. Visitor

[1] Note that we assume that coral reefs respond as fast to falling acidity as to rising acidity. This assumption may be optimistic, although one would expect an eventual positive effect from falling ocean acidity.

[2] Using the ReefBase database: http://www.reefbase.org/global_database/default.aspx

[3] That is Canada, USA, Western Europe, Japan and South Korea, Australia and New Zealand, Eastern Europe, former Soviet Union, Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. See http://www.fund-model.org/

numbers rapidly rise as people become more affluent and take more holidays. In the SRES scenarios, economic growth is concentrated in the poor countries in the tropics – exactly where coral reefs tend to be as well. The HTM model assumes that mass tourism will remain at destinations that are not too far from the home country, so that tourism growth is also concentrated in the tropics. However, the elasticity is only 0.68. The fourth development dominates. The SRES scenarios have rapid growth in poor countries, and the income elasticity of the coral reef value is 1.2. This explains the explosive growth in value.

Figure 7 shows the *annual* economic damage of ocean-acidification-induced coral reef loss. Figure 7 multiplies Figure 5 (area loss) and Figure 6 (net present value per area).[4] Damages are higher in the A1 and B2 scenarios than in the A2 scenario because values are higher in A1 and B2 than in A2. The B2 scenario has both lower values and lower loss than the A1 scenario. In the long run, the B1 scenario has the lowest damages, because it has the lowest loss of coral reefs; following the coral loss scenarios, there are even benefits towards the end of the century. The annual damage goes up to $870 billion in the A1 scenario in 2100. Although this may seem a substantial economic loss, this damage figure is only 0.14% of global GDP. The proportional loss in the B2 scenario is in fact higher (0.18% of GDP), while the A2 scenario is again lower (0.14% of GDP).

Figure 8 shows a sensitivity analysis of the annual damage in 2100. The B2 scenario is central in most cases, so we varied parameters in that scenario. Parameters were varied by one standard deviation. For comparison, the results of the other three scenarios are also shown. The response of ocean acidity to ambient carbon dioxide concentrations is not particularly uncertain, and damages are hardly affected. The area elasticity of value is not that important either. The extent of coral area loss per unit change in ocean pH is very uncertain, however, and this uncertainty is about as large as the uncertainty about the scenarios. The largest uncertainty, more than a factor four, is the value per unit area.

5. Discussion and conclusion

This paper gives the first estimate of the economic value of ocean acidification. Although this estimate is limited to the impact on coral reefs, perhaps the most tractable of the many

[4] Multiplying the annual value per area of coral reef with the total coral reef loss until a particular year assumes perpetual regret – that is, people in 2100 still suffer a loss of welfare because of coral reef loss in 2000, and the 2100 loss is in fact greater than the 2000 loss because of economic growth etc.

impacts of ocean acidification. We construct and calibrate simple models of ocean acidification and coral reef area loss, driven by the atmospheric concentration of carbon dioxide. We extend an earlier meta-analysis of coral reef values to estimate a value transfer function for coral reefs, and apply an existing model of tourist numbers. The FUND model is used to estimate CO_2 emissions for the four SRES scenarios. Combining these models, we derive a number of scenarios of the annual impact of ocean-acidification-induced coral reef loss, and conduct a sensitivity analysis.

We find that the annual economic impact rapidly escalates over time, essentially because the scenarios have rapid economic growth in the relevant countries and coral reefs are a luxury good. Nonetheless, the annual value in 2100 in still only a small fraction of total income, and one order of magnitude smaller than the impact of climate change (Tol 2008b). The estimated impact is uncertain, of course, but the estimated confidence interval spans one order of magnitude only.

Despite the relatively small numbers, future research should investigate the implications of our findings for climate policy – the Pigouvian tax on carbon dioxide emissions, the trade-offs between greenhouse gases, the optimal trajectory over time and its sensitivity to the discount rate, and the attractiveness of geoengineering. If indeed ocean acidification adds some 10% to the total impact of climate change, then the Pigouvian tax on carbon dioxide (but not on other greenhouse gases) should go up by at least 10% too. However, as ocean acidification is a more direct and more immediate impact, the marginal cost estimate should be more sensitive than the total cost estimate – but how much remains to be studied. To test the robustness of our conclusions, other researchers should derive their own estimates of the economic value of ocean acidification. Future research should seek to extend the estimates presented here to other impacts of ocean acidification, notably on shellfish, fish, marine mammals, and birds; and to investigate the interactions between ocean acidification, climate change, and sea level rise.

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References

Nakicenovic, N. and R.J.Swart (eds.) (2001), *IPCC Special Report on Emissions Scenarios* Cambridge University Press, Cambridge.

Andersson, A.J., N.R.Bates, and F.T.MacKenzie (2007), 'Dissolution of Carbonate Sediments under Rising pCO_2 and Ocean Acidification: Observations from Devil's Hole, Bermuda', *Aquatic Geochemistry*, **13**, 237-264.

Andersson, A.J., F.T.MacKenzie, and L.M.Ver (2003), 'Solution of Shallow-Water Carbonates: An Insignificant Buffer Against Rising Atmospheric CO_2', *Geology*, **31**, (6), 513-516.

Brander, L.M., P.J.H.van Beukering, and H.S.J.Cesar (2007), 'The Recreational Value of Coral Reefs: A Meta-Analysis', *Ecological Economics*, **63**, 209-218.

Burke, L. and J.Maidens (2004), *Reefs at Risk in the Caribbean* ,World Resources Institute, Washington,D.C.

Caldeira, K. and M.E.Wickett (2005), 'Ocean Model Predictions of Chemistry Changes from Carbon Dioxide Emissions to the Atmosphere and Ocean', *Journal of Geophysical Research*, **110**, (C09S04).

Cao, L., K.Caldeira, and A.K.Jain (2007), 'Effects of Carbon Dioxide and Climate Change on Ocean Acidification and Carbonate Mineral Saturation', *Geophysical Research Letters*, **34**, (L05607), 1-5.

Castles, I. and D.Henderson (2003), 'The IPCC Emission Scenarios: An Economic-Statistical Critique', *Energy & Environment*, **14**, (2-3), 159-185.

Cesar, H.S.J., L.Burke, and L.Pet-Soede (2003), *The Economics of Worldwide Coral Reef Degradation* ,Cesar Environmental Economic Consulting, Arnhem.

d'Arge, R., W.D.Schulze, and D.S.Brookshire (1982), 'Carbon Dioxide on Intergenerational Choice', *American Economic Review*, **72**, (2), 251-256.

Gattuso, J.-P., M.Frankignoulle, I.Bourge, S.Romaine, and R.W.Buddemeier (1998), 'Effect of Calcium Carbonate Saturation of Seawater on Coral Calcification', *Global and Planetary Change*, **18**, 37-46.

Gazeau, F., C.Quiblier, J.M.Jansen, J.-P.Gattuso, J.J.Middelburg, and C.H.R.Heip (2007), 'Impact of Elevated CO2 on Shellfish Calcification', *Geophysical Research Letters*, **34**, (L07603), 1-5.

Gibson, T., H.Wanless, J.Klaus, P.Foster-Turley, K.Florini, and T.Olso (2008), *Corals and Climate Change: Florida's National Treasures at Risk* ,Environmental Defense Fund, Washington, D.C.

Hall-Spencer, J.M., R.Rodolfo-Metalpa, S.Martin, E.Ransome, M.Fine, S.M.Turner, S.J.Rowley, D.Tedesco, and M.-C.Buia (2008), 'Volcanic Carbon Dioxide Vents Show Ecosystem Effects of Ocean Acidification', *Nature*, **454**, 96-99.

Hamilton, J.M., D.J.Maddison, and R.S.J.Tol (2005), 'Effects of Climate Change on International Tourism', *Climate Research*, **29**, 245-254.

Hoegh-Goldberg, H. and O.Hoegh-Goldberg (2004), *The Implications of Climate Change for Australia's Great Barrier Reef: People and Industries at Risk* ,World Wildlife Fund and Queensland Tourism Industry Council, Brisbane.

Hoegh-Goldberg, O., P.J.Mumby, A.J.Hooten, R.S.Steneck, P.Greenfield, E.Gomez, C.D.Harvell, P.F.Sale, A.J.Edwards, K.Caldeira, N.Knowlton, C.M.Eakin, R.Iglesias-Prieto, N.Muthiga, R.H.Bradbury, A.Dubi, and M.E.Hatziolos (2007), 'Coral Reefs under Rapid Climate Change and Ocean Acidification', *Science*, **318**, 1737-1742.

Ishimatsu, A., T.Kikkawa, M.Hayashi, K.-S.Lee, and J.Kita (2004), 'Effects of CO2 on Marine Fish: Larvae and Adults', *Journal of Oceanography*, **60**, 731-741.

Key, R.M., A.Kozyr, C.L.Sabine, K.Lee, R.Wanninkhof, J.L.Bullister, R.A.Feely, F.J.Millero, C.Mordy, and T.H.Peng (29-12-2004), 'A global ocean carbon climatology: Results from Global Data Analysis Project (GLODAP)', *Global Biogeochem.Cycles*, **18**.

Kleypas, J.A., R.W.Buddemeier, D.Archer, J.-P.Gattuso, C.Langdon, and B.N.Opdyke (1999), 'Geochemical Consequences of Increased Atmospheric Carbon Dioxide on Coral Reefs', *Science*, **284**, 118-120.

Langdon, C., T.Takahashi, C.Sweeney, D.Chipman, J.Goddard, F.Marubini, H.Aceves, H.Barnett, and M.J.Atkinson (2000), 'Effect of Calcium Carbonate Saturation State on the Calcification Rate of an Experimental Coral Reef', *Global Biogeochemical Cycles*, **14**, (2), 639-654.

Maier-Reimer, E. and K.Hasselmann (1987), 'Transport and Storage of Carbon Dioxide in the Ocean: An Inorganic Ocean Circulation Carbon Cycle Model', *Climate Dynamics*, **2**, 63-90.

McNeil, B.I. and R.J.Matear (2006), 'Projected Climate Change Impact on Oceanic Acidification', *Carbon Balance and Management*, **1**, (2), 1-6.

McNeil, B.I. and R.J.Matear (2007), 'Climate Change Feedbacks on Future Oceanic Acidification', *Tellus*, **59B**, 191-198.

Morse, J.W., A.J.Andersson, and F.T.MacKenzie (2006), 'Initial Responses of Carbonate-Rise Shelf Sediments to Rising Atmospheric pCO_2 and "Ocean Acidification": Role of High Mg-Calcites', *Geochimica et Cosmochimica Acta*, **70**, 5814-5830.

Nordhaus, W.D. (1991), 'To Slow or Not to Slow: The Economics of the Greenhouse Effect', *Economic Journal*, **101**, 920-937.

Orr, J.C., V.J.Fabry, O.Aumont, L.Bopp, S.C.Doney, R.A.Feely, A.Gnanadesikan, N.Gruber, A.Ishida, F.Joos, R.M.Key, K.Lindsay, E.Maier-Reimer, R.Matear, P.Monfray, A.Mouchet, R.G.Najjar, G.-K.Plattner, K.B.Rodgers, C.L.Sabine, J.L.Sarmiento, R.Schlitzer, R.D.Slater, I.J.Totterdell, M.-F.Weirig, Y.Yamanaka, and A.Yool (2005), 'Anthropogenic Ocean Acidification over the Twenty-First Century and its Impact on Calcifying Organisms', *Nature*, **437**, 681-686.

Pielke, R.A., Jr., T.M.L.Wigley, and C.Green (2008), 'Dangerous Assumptions', *Nature*, **452**, 531-532.

Ridgwell, A., I.Zondervan, J.C.Hargreaves, J.Bijma, and T.M.Lenton (2007), 'Assessing the Potential Long-Term Increase of Oceanic Fossil Fuel CO_2 Uptake due to CO_2-Calcification Feedback', *Biogeosciences*, **4**, 481-492.

Riebesell, U., I.Zondervan, B.Rost, P.D.Tortell, R.E.Zeebe, and F.M.M.Morel (2000), 'Reduced Calcification of Marine Plankton in Response to Increased Atmospheric CO2', *Nature*, **407**, 364-367.

Schelling, T.C. (1996), 'The Economic Diplomacy of Geoengineering', *Climatic Change*, **33**, 303-307.

Schmalensee, R. (1993), 'Comparing Greenhouse Gases for Policy Purposes', *Energy Journal*, **14**, 245-255.

Spicer, J.I., A.Raffo, and S.Widdicombe (2007), 'Influence of CO_2-Related Seawater Acidification on Extracellular Acid-Base Balance in the Velvet Swimming Crab *Necora Puber*', *Marine Biology*, **151**, 1117-1125.

Tol, R.S.J. (2005), 'The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties', *Energy Policy*, **33**, 2064-2074.

Tol, R.S.J. (2008a), 'Climate, development and malaria: An application of FUND', *Climatic Change*, **88**, (1), 21-34.

Tol, R.S.J. (2008b), 'Why Worry About Climate Change? A Research Agenda', *Environmental Values*, **17**, (4), 437-470.

Vergara, W., N.Toba, D.Mira-Salama, and A.Deeb (2009), 'The Potential Consequences of Climate-Induced Coral Loss in the Caribbean by 2050-2080', in *Assessing the Potential Consquences of Climate Destabilization in Latin America*, vol. 32 W. Vergara (ed.), World Bank, Washington, D.C..

Westmacott, S., H.S.J.Cesar, L.Pet-Soede, and O.Linden (2002), 'Coral Bleaching in the Indian Ocean: Socio-Economic Assessment of the Effects', in *Collected Essays on the Economics of Coral Reefs*, H.S.J. Cesar (ed.), Kalmar University, Kalmar.

Wilkinson, C., O.Linden, H.S.J.Cesar, G.M.Hodgson, J.Rubens, and A.E.Strong (1999), 'Ecological and Socioeconomic Impacts of 1998 Coral Mortality in the Indian Ocean: An ENSO Impact and a Warning of Future Change?', *Ambio*, **28**, 188-199.

World Bank (2000), Cities, Sea, and Storms: Managing Change in Pacific Island Economies. Volume IV: Adapting to Climate Change Change ,Papua New Guinea and Pacific Islands Country Unit, World Bank, Washington, D.C.

Table 1. The impact of ocean acidification on coral reef area according to five studies. The implied logistic parameter γ (Equation 2) is also given.

Coral area change (fraction)	CO_2 (ppm)	Acidity (pH)	γ	Source
-0.40	700	-0.33	0.88	Andersson *et al*. (2007)
-0.07	700	-0.33	0.20	Andersson *et al*. (2003)
-0.44	700	-0.33	0.94	Andersson *et al*. (2003)
-0.03	560	-0.25	0.12	Gattuso *et al*. (1998)
-0.16	1000	-0.47	0.30	Gattuso *et al*. (1998)
-0.08	560	-0.25	0.30	Kleypas *et al*. (1999)
-0.17	560	-0.25	0.59	Kleypas *et al*. (1999)
-0.40	560	-0.25	1.15	Langdon *et al*. (2000)

Table 2. Meta-regression results; dependent variable is ln(coral reef value per square kilometer).

Category	Variable	Coefficient	Standard deviation
	Constant	0.216	5.298
Socio-economic	GDP per capita (ln)	1.125*	0.573
	Population density (ln)	0.516*	0.282
	Visitors (ln)	0.675***	0.129
Location	USA	-3.604**	1.457
	East Africa	-0.200	1.706
	South East Asia	-4.606**	1.614
	Australia	-6.725**	2.779
Reef quality	Area coral cover (ln)	-0.524***	0.092
	Biodiversity index (ln)	2.475**	1.000
Goods and services	Dive tourism	0.355	0.505
	Snorkelling	-0.605*	0.427
	Other reef tourism	0.535*	0.466
	Commercial fishing	-0.390	0.758
	Recreational fishing	-1.192	1.656
	Coastal protection	-3.061*	1.757
	Biodiversity	0.638	1.656
	Preservation	0.148	1.119
Valuation method	CVM	-1.701*	1.649
	Travel cost method	0.405	1.708
	Net factor income	-1.377	1.797
	Production function method	-0.512	1.928
	Gross revenue	-0.281	1.703
Adj. R^2	0.601	F	6.553
Standard error	1.510	N	81

*** p<0.01, ** p<0.05, * p<0.1

Table A1. Descriptive statistics for the variables in the meta-regression (cf. Table 1)

	Mean	Std. Deviation
US$ per km2 per year (ln)	10.946	2.392
GDP per capita (ln)	9.141	1.275
Population density (ln)	3.924	1.374
Visitors (ln)	11.514	2.312
US	0.366	0.485
East Africa	0.110	0.315
SE Asia	0.256	0.439
Australia	0.098	0.299
Area coral cover (ln)	3.902	2.703
Biodiversity index (ln)	-1.290	0.773
Dive tourism	0.720	0.452
Snorkelling	0.561	0.499
Other reef tourism	0.451	0.501
Commercial fishing	0.073	0.262
Recreational fishing	0.012	0.110
Coastal protection	0.024	0.155
Biodiversity	0.012	0.110
Preservation	0.061	0.241
CVM	0.488	0.503
Travel cost method	0.134	0.343
Net factor income	0.085	0.281
Production function method	0.073	0.262
Gross revenue	0.207	0.408

Table A2. Selected characteristics of affected countries: Reef area in 2000; population, per capita income, and international tourist arrivals in 2000 and assumed growth rates for the 21st century.

	Reef	Population	Growth rate (%)				Income	Growth rate (%)				Arrivals	Growth rate (%)			
	km^2	000	A1	A2	B1	B2	$	A1	A2	B1	B2	000	A1	A2	B1	B2
Indonesia	51020	228438	0.20	0.68	0.20	0.68	1024	5.07	2.61	4.56	3.53	4324	5.00	3.79	4.83	4.39
Australia	48960	19358	-0.31	-0.09	-0.31	-0.09	20327	3.66	2.19	3.09	2.60	3726	3.58	3.00	3.33	3.29
New Caledonia	40000	205	0.76	0.97	0.76	0.97	7367	3.96	2.57	3.43	2.97	86	3.82	3.22	3.56	3.50
Paraguay	25060	5734	0.03	0.02	0.03	0.02	1860	1.87	0.86	1.34	1.11	438	2.09	1.79	1.82	1.94
Papua New Guinea	13840	5049	0.81	1.34	0.81	1.34	1172	3.67	1.88	3.71	2.20	42	4.51	3.55	4.66	3.80
Fiji	10020	844	0.24	0.59	0.24	0.59	2544	3.48	2.21	3.00	2.60	318	3.66	3.16	3.43	3.42
Maldives	8920	311	0.24	0.59	0.24	0.59	1088	3.11	1.91	2.64	2.30	315	3.09	2.64	2.85	2.91
Saudi Arabia	6660	22757	-0.15	-0.08	-0.15	-0.08	6886	4.11	2.52	3.61	3.27	3325	4.86	4.21	4.66	4.77
Marshall Islands	6110	71	0.24	0.59	0.24	0.59	1923	2.94	1.76	2.47	2.12	5	3.27	2.84	3.04	3.08
French Polynesia	6000	254	-0.01	-0.23	-0.01	-0.23	5095	1.95	0.85	1.48	1.16	172	3.01	2.58	2.75	2.87
India	5790	1029991	0.03	0.02	0.03	0.02	358	1.87	0.86	1.34	1.11	2124	1.95	1.68	1.69	1.83
Solomon Islands	5750	480	-0.15	-0.08	-0.15	-0.08	863	4.11	2.52	3.61	3.27	12	4.85	4.21	4.65	4.77
Vanuatu	4110	193	0.24	0.59	0.24	0.59	1402	3.48	2.21	3.00	2.60	44	3.57	3.09	3.36	3.33
Egypt	3800	69537	0.85	0.97	0.85	0.97	949	3.17	1.91	2.64	2.31	2872	3.72	3.28	3.47	3.56
Malaysia	3600	22229	0.20	0.68	0.20	0.68	4343	5.07	2.61	4.56	3.53	7469	5.33	4.12	5.16	4.75
Bahamas	3580	298	0.24	0.59	0.24	0.59	12338	3.48	2.21	3.00	2.60	1598	3.74	3.24	3.51	3.50
Tanzania, United Rep	3580	36232	-0.15	-0.08	-0.15	-0.08	155	4.11	2.52	3.61	3.27	285	4.21	3.56	4.02	4.11
Cuba	3290	11184	0.03	0.02	0.03	0.02	640	1.87	0.86	1.34	1.11	738	1.90	1.61	1.63	1.76
Eritrea	3260	4298	0.24	0.59	0.24	0.59	180	3.48	2.21	3.00	2.60	315	3.63	3.14	3.40	3.40
Kiribati	2940	94	0.81	1.34	0.81	1.34	616	4.67	2.67	4.71	2.99	4	4.89	3.78	5.05	4.02
Japan	2900	126772	0.24	0.59	0.24	0.59	40944	2.94	1.76	2.47	2.12	1731	3.16	2.73	2.95	2.96
Sudan	2720	36080	0.20	0.68	0.20	0.68	279	5.07	2.61	4.56	3.53	63	5.45	4.25	5.28	4.87
Madagascar	2230	15983	0.24	0.59	0.24	0.59	230	3.11	1.91	2.64	2.30	75	3.50	3.06	3.26	3.32
Thailand	2130	61798	-0.31	-0.09	-0.31	-0.09	2869	3.66	2.19	3.09	2.60	6952	3.66	3.07	3.41	3.36
Colombia	2060	40349	0.81	1.34	0.81	1.34	2090	3.67	1.88	3.71	2.20	1399	4.31	3.38	4.48	3.62
Myanmar	1870	41995	0.24	0.59	0.24	0.59	556	3.11	1.91	2.64	2.30	110	3.41	2.87	3.16	3.17
Mozambique	1860	19371	0.01	0.39	0.01	0.39	111	3.31	1.67	2.67	2.60	51	3.85	3.18	3.53	3.90
Seychelles	1690	80	-0.31	-0.09	-0.31	-0.09	6920	3.66	2.19	3.09	2.60	121	3.57	2.99	3.32	3.28
Puerto Rico	1610	3937	0.81	1.34	0.81	1.34	4673	4.67	2.67	4.71	2.99	3131	4.82	3.70	4.97	3.94
Panama	1600	2846	0.81	1.34	0.81	1.34	3005	4.96	2.91	4.99	3.24	345	5.02	3.90	5.18	4.15
China	1510	1273111	0.01	0.39	0.01	0.39	574	3.93	2.17	3.27	3.18	20034	4.19	3.51	3.91	4.24
Tonga	1500	104	0.81	1.34	0.81	1.34	1692	4.67	2.67	4.71	2.99	29	4.92	3.81	5.08	4.06
Belize	1420	256	0.52	0.30	0.52	0.30	2775	1.86	0.86	1.40	1.13	131	2.36	2.07	2.15	2.23
Dominican Rep	1350	8582	0.81	1.34	0.81	1.34	1525	4.67	2.67	4.71	2.99	1776	4.91	3.79	5.06	4.03
Viet Nam	1270	79939	0.81	1.34	0.81	1.34	274	4.67	2.67	4.71	2.99	1351	4.92	3.82	5.08	4.06
Haiti	1260	6965	0.81	1.34	0.81	1.34	349	4.67	2.67	4.71	2.99	145	5.01	3.90	5.17	4.15
Mexico	1220	101879	0.24	0.59	0.24	0.59	3139	3.11	1.91	2.64	2.30	20241	3.56	3.08	3.31	3.36

	Reef	Population	Growth rate (%)				Income	Growth rate (%)				Arrivals	Growth rate (%)			
Brazil	1200	174469	-0.41	0.24	-0.41	0.24	4418	4.24	1.91	3.63	3.00	1991	4.41	3.18	4.14	3.92
United Arab Emirates	1190	2408	0.24	0.59	0.24	0.59	11786	3.11	1.91	2.64	2.30	1601	3.28	2.83	3.05	3.09
Palau	1150	19	0.81	1.34	0.81	1.34	3182	4.67	2.67	4.71	2.99	45	4.87	3.76	5.02	4.02
Honduras	1120	6406	0.81	1.34	0.81	1.34	702	4.67	2.67	4.71	2.99	215	4.59	3.49	4.75	3.73
Jamaica	1010	2657	0.81	1.34	0.81	1.34	1691	4.67	2.67	4.71	2.99	1147	4.55	3.45	4.71	3.69
Taiwan, Province of China	940	22371	0.24	0.59	0.24	0.59	8702	3.48	2.21	3.00	2.60	1553	3.67	3.17	3.44	3.43
Mauritius	870	1190	0.81	1.34	0.81	1.34	3561	4.67	2.67	4.71	2.99	422	4.64	3.53	4.80	3.77
Nicaragua	870	4918	-0.31	-0.09	-0.31	-0.09	426	3.66	2.19	3.09	2.60	281	3.42	2.84	3.17	3.12
United States	840	278959	0.24	0.59	0.24	0.59	26341	3.48	2.21	3.00	2.60	43385	3.63	3.14	3.41	3.39
Somalia	710	7489	0.03	0.02	0.03	0.02	199	1.87	0.86	1.34	1.11	10	2.38	2.11	2.11	2.26
Tuvalu	710	11	-0.31	-0.09	-0.31	-0.09	392	3.66	2.19	3.09	2.60	45	3.16	2.59	2.92	2.87
Iran, Islamic Rep	700	66129	0.03	0.02	0.03	0.02	1444	1.87	0.86	1.34	1.11	452	1.94	1.67	1.68	1.82
Qatar	700	769	0.81	1.34	0.81	1.34	10346	4.67	2.67	4.71	2.99	250	4.75	3.67	4.91	3.92
Yemen	700	18078	0.24	0.59	0.24	0.59	246	3.48	2.21	3.00	2.60	61	3.45	2.95	3.22	3.21
Sri Lanka	680	19409	0.24	0.59	0.24	0.59	726	3.48	2.21	3.00	2.60	403	3.77	3.27	3.54	3.53
Kenya	630	30766	0.01	0.39	0.01	0.39	333	3.93	2.17	3.27	3.18	691	4.30	3.52	3.99	4.28
Virgin Islands, U.S.	590	122	0.24	0.59	0.24	0.59	7367	3.11	1.91	2.64	2.30	454	3.41	2.96	3.17	3.22
Bahrain	570	645	0.76	0.97	0.76	0.97	9839	3.96	2.57	3.43	2.97	2043	4.06	3.48	3.80	3.77
Oman	530	2622	0.24	0.59	0.24	0.59	5615	3.48	2.21	3.00	2.60	352	3.57	3.07	3.34	3.33
Samoa	490	179	0.81	1.34	0.81	1.34	924	4.67	2.67	4.71	2.99	68	5.56	4.44	5.71	4.69
Djibouti	450	461	0.81	1.34	0.81	1.34	817	4.96	2.91	4.99	3.24	21	5.10	4.00	5.26	4.24
Cameroon	430	15803	-0.15	-0.08	-0.15	-0.08	604	4.11	2.52	3.61	3.27	100	4.26	3.60	4.06	4.16
Comoros	430	596	0.81	1.34	0.81	1.34	354	4.96	2.91	4.99	3.24	23	5.19	4.08	5.35	4.32
Guadeloupe	400	431	-0.01	-0.23	-0.01	-0.23	4152	1.95	0.85	1.48	1.16	640	2.90	2.46	2.64	2.74
Martinique	260	419	0.03	0.02	0.03	0.02	5201	1.87	0.86	1.34	1.11	457	2.21	1.94	1.95	2.10
Netherlands Antilles	250	212	0.03	0.02	0.03	0.02	5414	1.87	0.86	1.34	1.11	681	1.96	1.68	1.70	1.83
Venezuela	230	23917	0.24	0.59	0.24	0.59	3537	3.11	1.91	2.64	2.30	597	3.44	3.00	3.21	3.26
Bermuda	210	64	-0.01	-0.23	-0.01	-0.23	17849	1.95	0.85	1.48	1.16	387	2.88	2.43	2.62	2.70
Brunei Darussalam	210	344	0.81	1.34	0.81	1.34	16938	4.67	2.67	4.71	2.99	498	4.74	3.63	4.90	3.88
Antigua and Barbuda	180	67	0.81	1.34	0.81	1.34	3740	4.67	2.67	4.71	2.99	414	4.65	3.53	4.80	3.77
Grenada	160	89	-0.15	-0.08	-0.15	-0.08	2999	4.11	2.52	3.61	3.27	108	4.56	3.92	4.36	4.48
St. Kitts and Nevis	160	39	0.03	0.02	0.03	0.02	3132	1.87	0.86	1.34	1.11	232	2.07	1.80	1.81	1.96
St. Vincent & Grenadines	140	116	0.81	1.34	0.81	1.34	1120	4.67	2.67	4.71	2.99	60	4.87	3.75	5.02	3.99
Kuwait	110	2042	0.03	0.02	0.03	0.02	15719	1.87	0.86	1.34	1.11	295	2.34	2.06	2.07	2.22
Singapore	100	4300	0.24	0.59	0.24	0.59	25645	3.48	2.21	3.00	2.60	6422	3.79	3.29	3.56	3.55
Barbados	90	275	0.24	0.59	0.24	0.59	6594	3.48	2.21	3.00	2.60	442	3.72	3.22	3.49	3.47
St. Lucia	90	158	0.24	0.59	0.24	0.59	1825	3.48	2.21	3.00	2.60	256	3.50	3.01	3.27	3.27
Dominica	70	71	0.81	1.34	0.81	1.34	3140	4.67	2.67	4.71	2.99	60	4.87	3.75	5.01	3.99
Bangladesh	50	131270	0.81	1.34	0.81	1.34	317	4.67	2.67	4.71	2.99	156	4.24	3.13	4.39	3.37
Cambodia	50	12492	0.24	0.59	0.24	0.59	294	3.11	1.91	2.64	2.30	220	3.40	2.96	3.17	3.21
Ecuador	50	13184	0.24	0.59	0.24	0.59	1565	3.48	2.21	3.00	2.60	440	3.43	2.94	3.21	3.19

	Reef	Population	Growth rate (%)				Income	Growth rate (%)				Arrivals	Growth rate (%)			
Jordan	50	5153	0.24	0.59	0.24	0.59	1150	3.48	2.21	3.00	2.60	1074	3.48	2.99	3.25	3.25
Nauru	50	12	-0.41	0.24	-0.41	0.24	2147	3.60	1.46	3.00	2.45	190	3.89	2.90	3.63	3.62
Pakistan	50	144617	-0.31	-0.09	-0.31	-0.09	449	3.66	2.19	3.09	2.60	378	3.50	2.92	3.26	3.21
Reunion	50	733	0.03	0.02	0.03	0.02	2050	1.87	0.86	1.34	1.11	304	2.28	1.97	2.01	2.14
South Africa	50	43586	0.20	0.68	0.20	0.68	3566	5.07	2.61	4.56	3.53	4488	4.67	3.46	4.49	4.11
Trinidad and Tobago	40	1170	0.01	0.39	0.01	0.39	4202	3.93	2.17	3.27	3.18	260	4.04	3.29	3.74	4.01
Costa Rica	30	3773	0.85	0.97	0.85	0.97	2540	3.17	1.91	2.64	2.31	785	3.74	3.31	3.49	3.59
Israel	10	5938	0.85	0.97	0.85	0.97	15555	3.17	1.91	2.64	2.31	2212	3.56	3.10	3.30	3.39

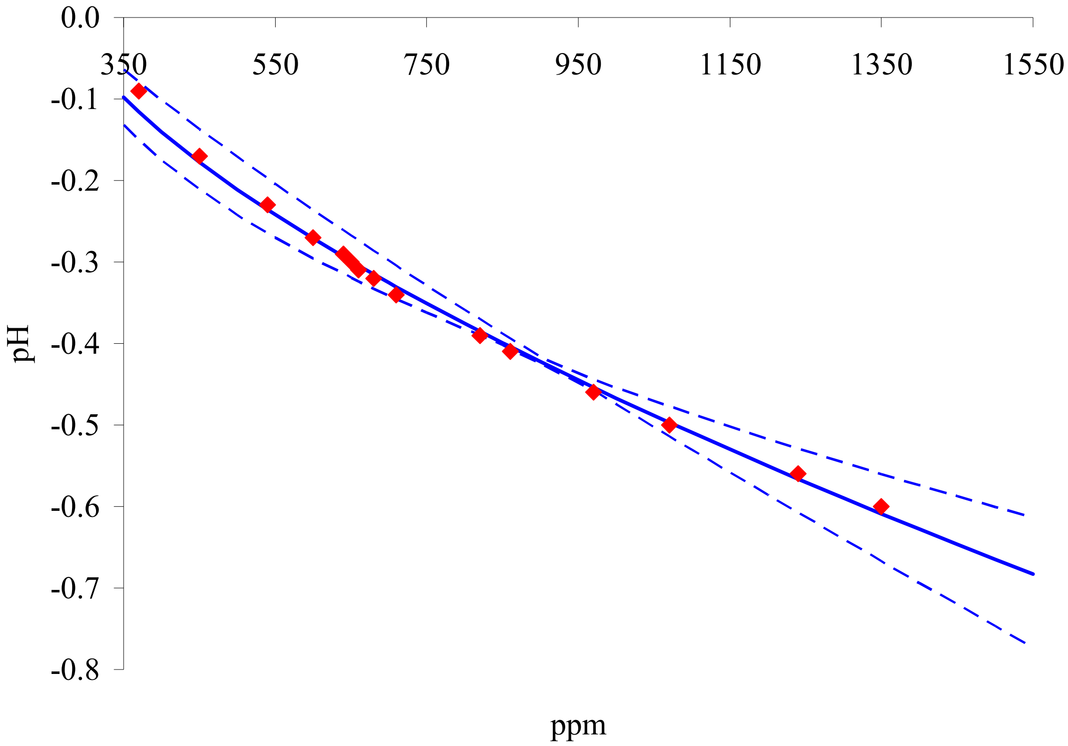

Figure 1. Ocean acidity as a function of the atmospheric concentration of carbon dioxide as modeled by Caldeira and Wickett (2005) (red squares) and as approximated by Equation (1) (thick blue line; the 67% confidence interval is given the dashed blue lines).

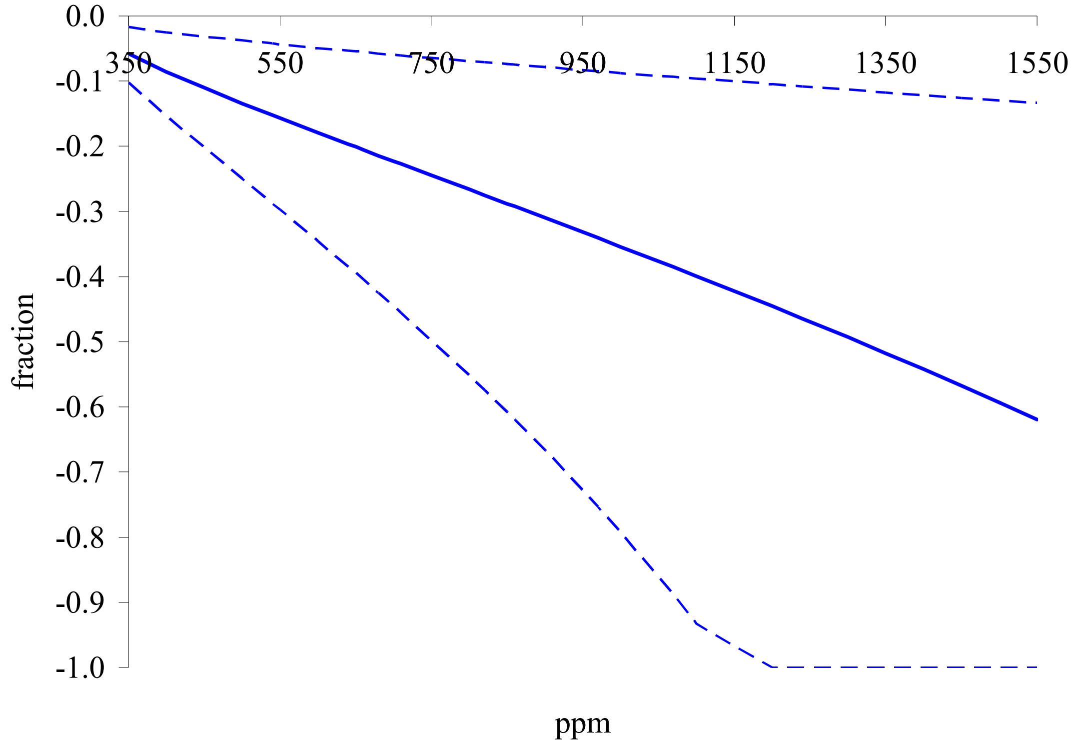

Figure 2. Coral reef area as a function of the atmospheric concentration of carbon dioxide as according to Equations (1) and (2). The dotted lines are the 67% confidence interval.

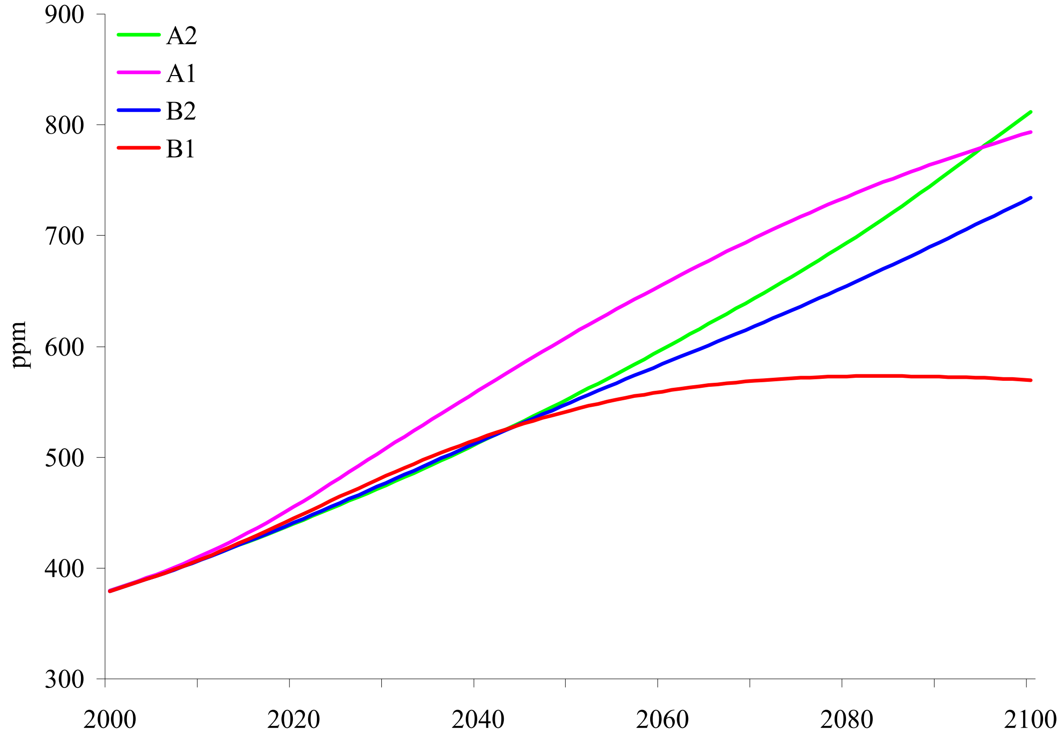

Figure 3. The atmospheric concentration of carbon dioxide according to the four SRES marker scenarios as implemented in FUND.

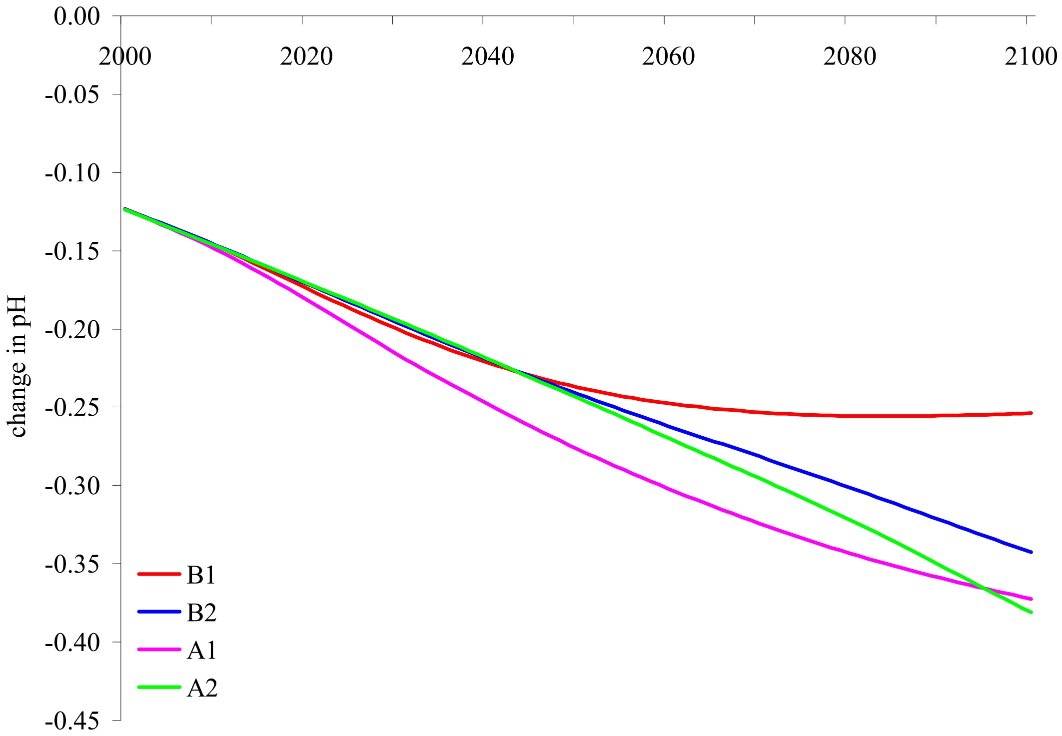

Figure 4. The change in ocean acidity according to the four SRES marker scenarios as implemented in FUND and Equation (1).

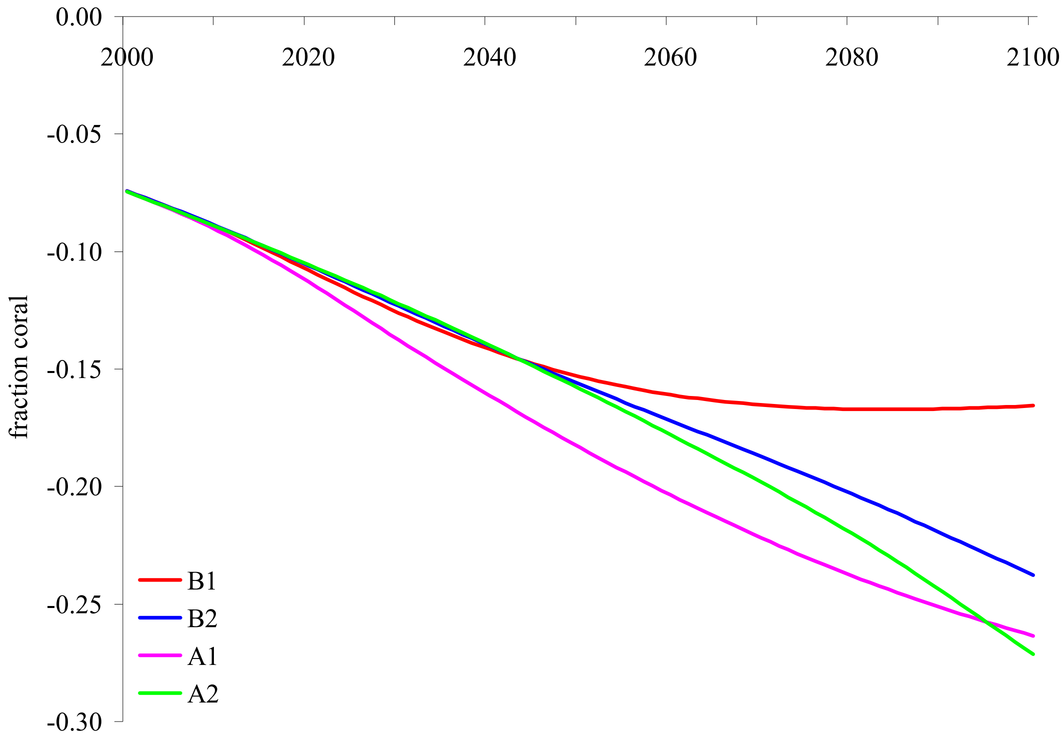

Figure 5. The change in coral reef area according to the four SRES marker scenarios as implemented in FUND and Equation (2).

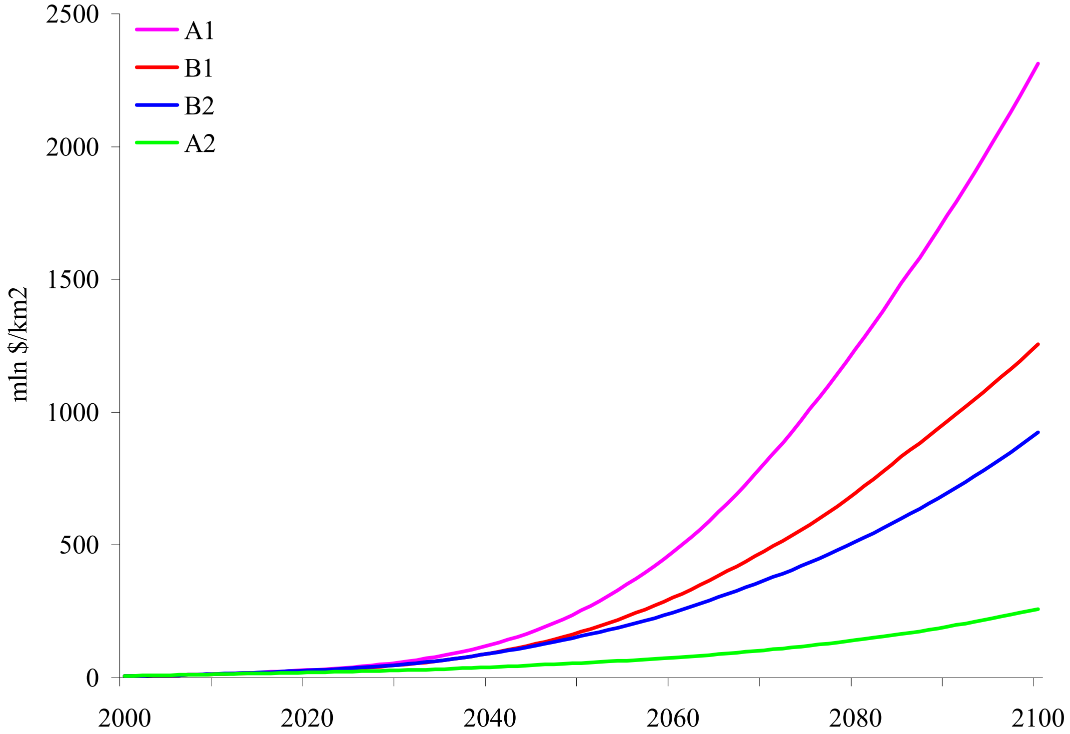

Figure 6. The net present value of coral reefs according to the four SRES marker scenarios as implemented in FUND and the meta-regression.

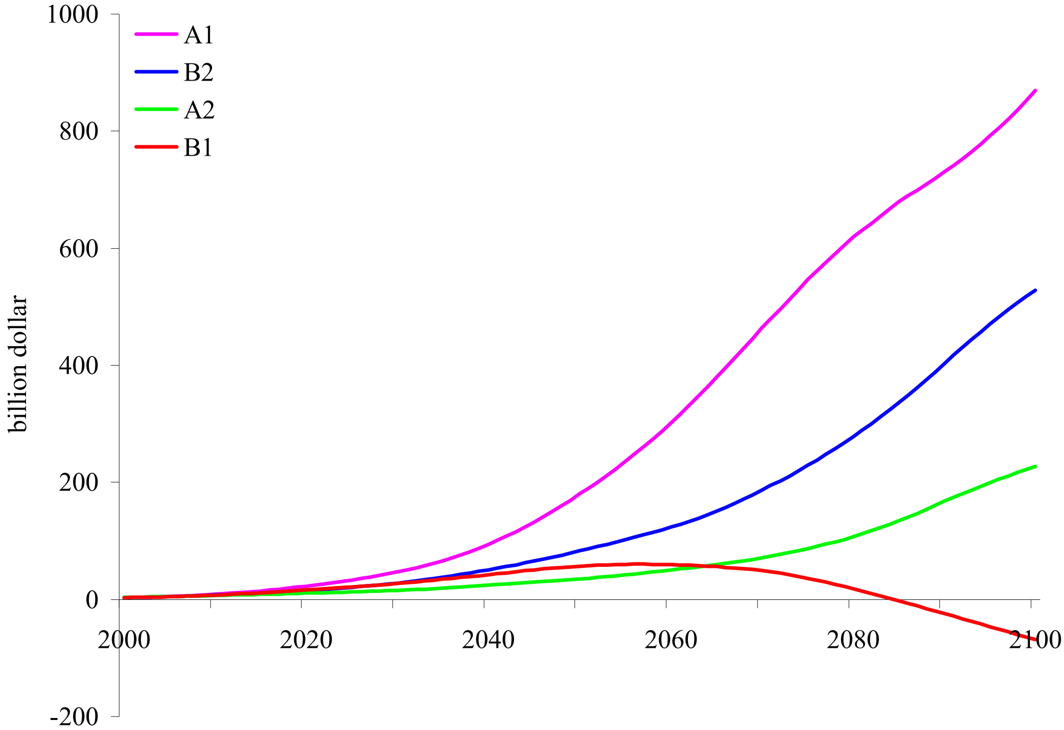

Figure 7. The annual economic damage of ocean-acidification-induced coral reef area loss.

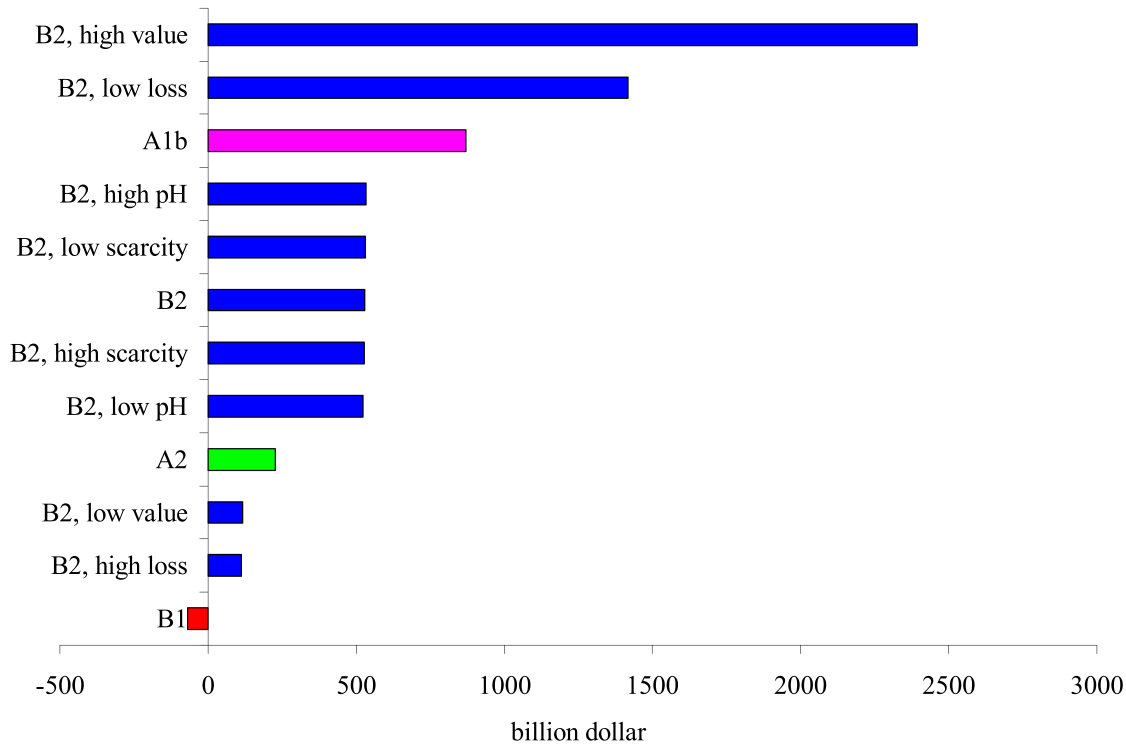

Figure 8. A sensitivity analysis around the annual economic damage of ocean-acidification-induced coral reef area loss.

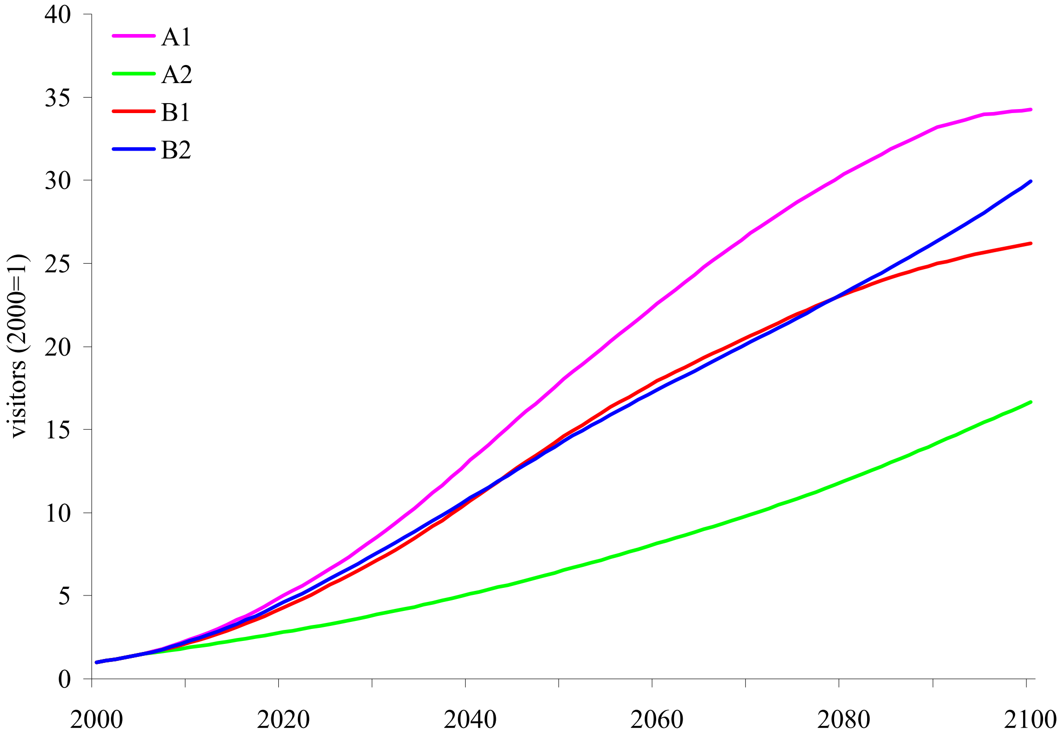

Figure A1. International visitors to coral reefs according to the four SRES marker scenarios as implemented in FUND and HTM.

Year	Number	Title/Author(s) ESRI Authors/Co-authors *Italicised*
2009		
	281	Assessing the impact of biodiversity on tourism flows: A model for tourist behaviour and its policy implications Giulia Macagno, Maria Loureiro, Paulo A.L.D. Nunes and *Richard S.J. Tol*
	280	Advertising to boost energy efficiency: the Power of One campaign and natural gas consumption *Seán Diffney, Seán Lyons* and *Laura Malaguzzi Valeri*
	279	International Transmission of Business Cycles Between Ireland and its Trading Partners *Jean Goggin* and *Iulia Siedschlag*
	278	Optimal Global Dynamic Carbon Taxation *David Anthoff*
	277	Energy Use and Appliance Ownership in Ireland *Eimear Leahy* and *Seán Lyons*
	276	Discounting for Climate Change *David Anthoff, Richard S.J. Tol* and Gary W. Yohe
	275	Projecting the Future Numbers of Migrant Workers in the Health and Social Care Sectors in Ireland *Alan Barrett* and Anna Rust
	274	Economic Costs of Extratropical Storms under Climate Change: An application of FUND Daiju Narita, *Richard S.J. Tol, David Anthoff*
	273	The Macro-Economic Impact of Changing the Rate of Corporation Tax *Thomas Conefrey* and *John D. Fitz Gerald*
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