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THE ECONOMIC IMPACT OF OCEAN ACIDIFICATION ON CORAL REEFS

LUKE M. BRANDER[*,†], KATRIN REHDANZ[‡,§,††],
RICHARD S. J. TOL[¶,||,**] and PIETER J. H. VAN BEUKERING[*]

[*]*Institute for Environmental Studies*
Vrije Universiteit, Amsterdam, The Netherlands

[†]*Division of Environment*
Hong Kong University of Science and Technology

[‡]*Kiel Institute for the World Economy, Kiel, Germany*

[§]*Department of Economics*
Christian-Albrechts-University of Kiel
Kiel, Germany

[¶]*Department of Economics, University of Sussex, United Kingdom*

[||]*Department of Spatial Economics*
Vrije Universiteit, Amsterdam, The Netherlands

[**]*Institute for Environmental Studies*
Vrije Universiteit, Amsterdam, The Netherlands
[††]*katrin.rehdanz@ifw-kiel.de*

Because ocean acidification has only recently been recognized as a problem caused by CO_2 emissions, 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 CO_2 is linked to ocean acidity causing coral reef area loss. Next, a meta-analytic value transfer 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.

Keywords: Ocean acidification; coral reefs; economic value.

JEL Classification: Q51, Q54, Q57

[††]Corresponding author.

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 dissolves to become an acid whose net effects on ocean chemistry are likely to cause ecosystems to shift away from calcifying species. While research on economic aspects of climate change has generated a large number of studies over the last few years, ocean acidification has only recently been recognised as a substantial problem. Impact studies are still rare and estimates of the economic impact are largely absent. We know of only three studies investigating economic consequences of ocean acidification on commercial fisheries, one focusing on the USA (Cooley and Doney, 2009) and two global studies (Cooley *et al.*, 2011; Narita *et al.*, 2012). Our study is the first to estimate 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 likely change the competition between marine plankton species in favor of those that rely less on calcium (Orr *et al.*, 2005; Riebesell *et al.*, 2000), negatively affect shellfish (Gazeau *et al.*, 2007; Spicer *et al.*, 2007), impact on fish (Munday *et al.*, 2009), may benefit highly invasive non-native algal species (Hall-Spencer *et al.*, 2008), and reduce coral calcification (Hoegh-Goldberg *et al.*, 2007; Veron *et al.*, 2009; Veron, 2011). 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 and Hoegh-Goldberg, 2004), Indian Ocean (Westmacott *et al.*, 2002; Wilkinson *et al.*, 1999), Pacific Ocean (World Bank, 2000); the Caribbean (Burke and Maidens, 2004; Vergara *et al.*, 2009) and the United States (Gibson *et al.*, 2008). Only Cesar *et al.* (2003a) 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 green-house 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 in the case that sulphur particles are used to cool the planet (Royal Society, 2009). 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.

In this study, we construct and combine a series of models that describe each step in the impact pathway between carbon dioxide emissions and economic impact on coral reef ecosystem services. The structure of this combined model is represented in Fig. 1.
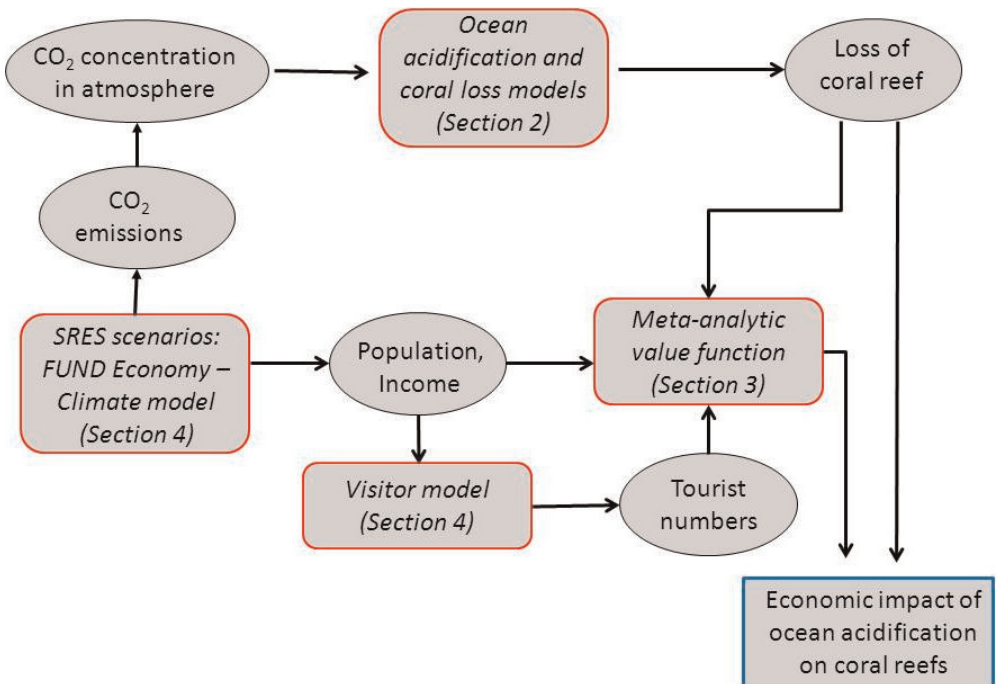

Figure 1. Model structure.

Subsequent sections of the paper describe the main elements of this model. 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 and 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 and Matear, 2006, 2007; Morse *et al.*, 2006; Ridgwell *et al.*, 2007). This allows us to approximate surface ocean acidity as a simple function of the atmospheric concentration of CO_2:

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

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 $\alpha = 0.00569$ (0.04 10^{-3}) and $\beta = 0.67$ (0.53–0.86) are based on OLS regression using the results of (Caldeira and Wickett, 2005). Figure 2 shows that Eq. (1) is a rather good approximation; the R^2 is 99.9%.

A number of studies has estimated the impact of ocean acidification on the calcification rate of coral reefs (Gattuso *et al.*, 1998; Kleypas *et al.*, 1999; Langdon *et al.*,
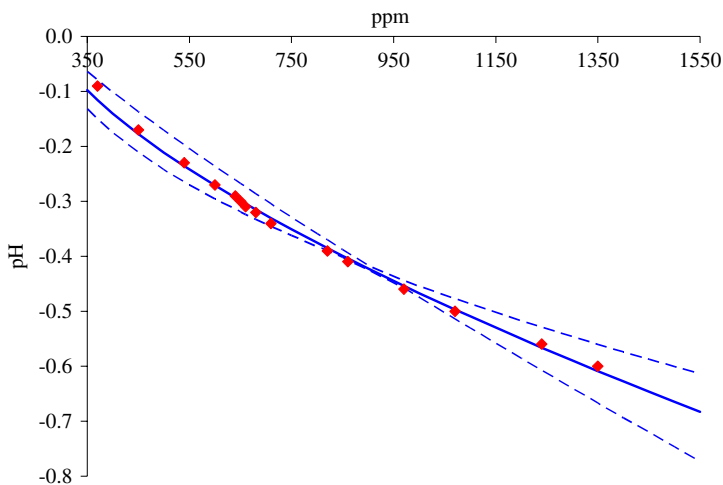

Figure 2. Ocean acidity as a function of the atmospheric concentration of carbon dioxide as modeled by Caldeira and Wickett (2005) and as approximated by Eq. (1) (thick line; the 67% confidence interval is given by the dashed lines).

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

Coral area change (fraction)[a]	CO_2 (ppmv)	Acidity (pH)[b]	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)

[a]Numbers are reported as changes in the rate of calcification.
[b]Own calculations based on Eq. (1).

2000; Andersson *et al.*, 2003, 2007). Table 1 summarizes their results, expressed as a loss in reef area.[1] We assume that reef area is a logistic function in ocean acidity:

$$R_t = \frac{\gamma A_t}{1 + \gamma A_t} \tag{2}$$

where R is the change in reef area since pre-industrial times, and $\gamma = 0.56$ (0.39) is a parameter; its value is the average of the parameters in Table 1.

Figure 3 gives reef area as a function of the atmospheric concentration of carbon dioxide, using Eq. (1) to compute ocean acidity. The uncertainty shown is the
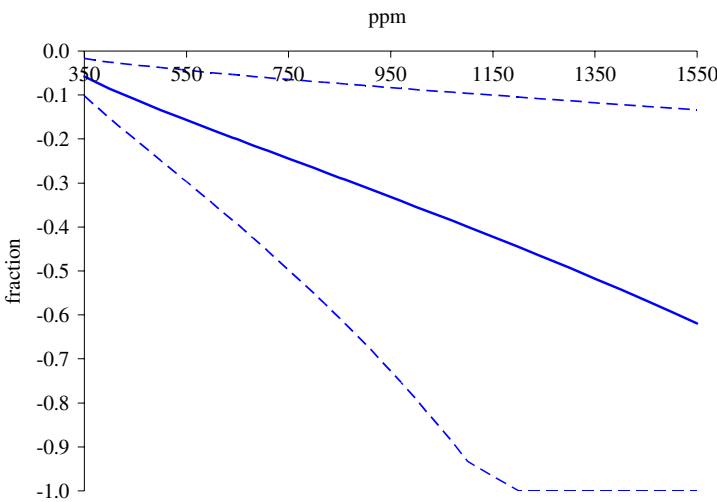

Figure 3. Coral reef area as a function of the atmospheric concentration of carbon dioxide as according to Eqs. (1) and (2). The dotted lines are the 67% confidence interval.

[1]We assume, for want of an alternative, that the loss in reef area is equal to the change in calcification rate.

uncertainty about the coral reef response to acidification only; this uncertainty is substantial. Recently published research has shown the impact of ocean acidification on coral reefs to be highly complex and that at the local habitat/reef scale there are biological mechanisms that potentially improve conditions for calcification depending on benthic community structure, reef size, water residence time and circulation patterns (Anthony *et al.*, 2011; Kleypas *et al.*, 2011). According to the information we used, at around 1200 ppmv, there is a 16.5% chance that coral reefs are so degraded that they are not able to reproduce successfully. However, it is beyond the scope of this paper to predict when coral reefs may become 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 including e.g., commercial fishing and coastal protection 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. The literature search attempted to be as comprehensive as possible by accessing online reference inventories (e.g., EVRI and ENVALUE), library catalogs, and relevant reference lists and bibliographies. Care was taken not to double count value estimates that are reported in more than one study, or to include estimates that were derived through value transfer. 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 i.e., contained information on all variables included in the meta-regression. From these 45 studies we were able to code 81 separate value observations, taking multiple observations from single studies (see Table A1 in the Appendix). On average, 1.8 observations per study were obtained, with a maximum of 12 observations from a single study (Cesar *et al.*, 2003a,b).

Regarding the geographic representation of the sample, 30 observations are for US coral reefs, 21 from Southeast Asia, 9 from East Africa, 8 from Australia and 13 from the Caribbean. In terms of the ecosystem services valued, the sample contains 71 value observations for recreational opportunities, 5 for indirect use values (commercial fishing, coastal protection) and 5 for non-use (existence) values. This distribution of available information for coral reef services has implications for the specification of the meta-analytic value function and the values that are subsequently transferred.[2]

The value observations have been estimated using a variety of valuation methods. Around half (41) were obtained using the contingent valuation method,[3] with the remainder derived from the travel cost (11), net factor income (7), production function (6), and gross revenue methods (17). It should be noted that these valuation methods differ significantly in terms of the welfare measures that they estimate (see Kopp and Smith, 1993; Carson *et al.*, 1996; Freeman, 2003). This source of heterogeneity in the data may lead to problems of non-comparability between estimated values and we need to be wary of comparing inconsistent concepts of economic value (Brouwer, 2000; Smith and Pattanayak, 2002).

The diversity in welfare measures being estimated makes it necessary to clearly distinguish between the different valuation techniques in the meta-analysis. Although we may have *a priori* expectations as to the direction of any bias associated with each valuation method (Bateman and Jones, 2003), it is not possible to make sensible adjustments to the observed valuation estimates to correct for these biases. We therefore include dummy variables for each valuation method in the meta-regression to control for differences in values estimated through each method. To some extent there is a correspondence between the coral reef service valued and the valuation method employed, i.e., some methods are more suited to valuing certain services than others. There is not, however, perfect correlation between methods and services, and so we include sets of dummy variables in the meta-regression to represent both methods and services.

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 standardized these values to a common metric, which is US\$/km^2/year in 2000 prices. The unit of area

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[2]The limited number of value observations for non-tourism/recreation services means that it is only possible to estimate an aggregate value function for all coral reef services. Ideally it would be possible to estimate separate value functions for each ecosystem service (or a system of value functions) to allow for variation in the influence of explanatory variables across services. As the number of estimates on the value of coral reef ecosystem services increases, particularly for non-tourism related services, it will become possible to conduct new analyses that examine each service separately.

[3]The contingent valuation method is considered to be less reliable in cases where respondents are unfamiliar with the valued good or service. Our sample, however, is dominated by studies that investigate the direct use value of coral reefs (e.g., recreational services), for which the targeted respondents are highly familiar.

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 selection of the units in which to standardise coral reef value estimates required careful assessment of the underlying data. Standardizing values to WTP per person as in Brouwer *et al.* (1999) or WTP per visit as in Brander *et al.* (2007) was not possible because several of the valuation methods used in the literature (e.g., net factor income, production function, and gross revenue methods) do not produce WTP estimates. WTP per person or per visit on the other hand could be converted to US\$/km^2/year given information on the area of coral cover and the relevant population size or number of visitors. We therefore followed Woodward and Wui (2001) and Brander *et al.* (2006) in defining the valuation effect size in terms of units of area. A further consideration in defining the units in which to standardize value estimates is that for the purposes of using the estimated meta-regression function for value transfer, it is preferable to define the dependent variable in per unit area rather than per person terms. This avoids the potentially difficult step in a value transfer exercise of identifying the number of beneficiaries that hold values for the policy site coral reef. Instead, the effect of beneficiary numbers on the value of coral reefs is controlled for by including population and visitor variables in the meta-regression.

In standardizing coral reef values we face the problem of distinguishing between average and marginal values, both of which can be expressed as a monetary value per km^2. The majority of coral reef valuation studies have estimated total or average values but there are also a number of estimates of marginal values. Expressing coral reef values in per km^2 terms gives the impression that each km^2 of coral cover is equally productive, i.e., exhibit constant returns to scale or equivalently that the marginal value is equal to the average value. Without being able to convert marginal values to average values or *vice versa*, we assume exactly this. This assumption is examined by including the area of coral cover as an explanatory variable in the meta-regression. Information on the area of coral cover was obtained from the underlying valuation studies; gaps in this information were filled using a number of site-specific sources.

The methodological approach that we use to explain 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 in estimates across studies (Stanley, 2001). 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 for four different regions), ecological (area of coral cover and an index for biodiversity), socio-economic (GDP per capita, population density and number of visitors), services provided by the reef based on the valuation studies (e.g., dive tourism, snorkeling, commercial and recreational fishing and coastal protection), and methodological variables (valuation method used). The biodiversity index is defined as a composite measure of coral diversity and

reef fish diversity. Information on population density was derived from Center for International Earth Science Information Network (CIESIN) data. The process by which this data was converted to represent each coral reef valuation site is described in Wagtendonk and Omtzigt (2003). Visitor numbers of each site were obtained either directly from each valuation study or from site specific sources. Table A2 in the Appendix provides definitions and descriptive statistics of the dependent and explanatory variables included in the meta-regression.

A number of alternative model specifications were investigated before defining the estimated meta-regression model given in Eq. (3). The dependent variable (y) in the meta-regression is a vector of values in US\$/km^2/year in 2000 prices. The explanatory variables are the socio-economic characteristics X_E (i.e., GDP per capita, population, and visitors), location X_L, reef quality X_R (i.e., area of coral cover, biodiversity index), services values X_S, and the valuation methods used X_V. a is the constant term; b_E, b_L, b_R, b_S, and b_V contain the estimated coefficients on the respective explanatory variables; and μ is a vector of residuals with assumed well behaved underlying errors. The natural logarithms of the continuous variables (indicated in Table 2) are used in order to improve model fit and mitigate heteroskedasticity.

$$\ln(y) = a + b_E X_E + b_L X_L + b_R X_R + b_S X_S + b_V X_V + \mu \qquad (3)$$

The results of the meta-regression are presented in Table 2. A series of diagnostic tests were performed in order to test the robustness of the OLS estimation. The Kolmogorov-Smirnov test (K-S statistic $= 0.072$) does not reject the assumption of normally distributed residuals. Similarly, the null hypothesis of homogenous variance of the residuals cannot be rejected by White's test for heteroskedasticity (White's statistic $= 12.841$). Regarding model specification, the regression specification error test (RESET statistic $= 0.253$) does not reject the null hypothesis that the estimated linear form is the correct specification of the model. We test for potential multicollinearity in the model using pairwise correlations between the explanatory variables and find no correlation coefficients in excess of 0.8. 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. This may reflect the relative travel time and cost to international reef visitors. As one would expect, income per capita, population density, and the number of visitors all have positive effects on coral reef value. More

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

Category	Variable	Coefficient	Standard deviation
Socio–economic	Constant	0.216	5.298
	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
	Southeast 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
Services	Dive tourism	0.355	0.505
	Snorkeling	−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

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

biodiverse reefs are more valuable, and smaller reefs are more valuable (per square kilometer) than are bigger reefs, again as one would expect. The latter result indicates diminishing returns to scale of coral cover, i.e., that adding an additional km^2 to a large area of coral cover has a lower value than an additional km^2 to a small area. *Vice versa*, losing a km^2 from a small area is more serious than losing a km^2 from a large area. The 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. In the next section we use the estimated meta-analytic value function to conduct a value transfer to global coral reefs.

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 and Swart, 2001). Although controversial (Castles and Henderson, 2003; Pielke *et al.*, 2008), the SRES scenarios are the standard in climate change impact analysis. Table A3 in the Appendix shows the scenario characteristics of the affected countries, that is, those with coral reefs.

Figure 4 shows the atmospheric concentration of carbon dioxide according to the four SRES scenarios and a standard (Maier-Reimer and 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 ppmv (and falling) in the B1 scenario to 812 ppmv (and accelerating) in A2.

Figure 5 shows the resulting change in surface ocean pH. Equation (1) has that ocean pH is proportional to the excess atmospheric concentration of carbon dioxide, raised to the power 2/3. In pre-industrial time, ocean pH was 8.2 (Key *et al.*, 2004). There is a wide range for future pH values. 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 Fig. 3.

Figure 6 shows the percentage loss of coral reef area (since pre-industrial times) due to the increased acidity of the surface ocean. Equation (2) has a logistic relationship between ocean pH and coral reef area, so the response is monotone but non-linear. In 2000, the total area was some 307,000 km^2, but already 7% was lost due to
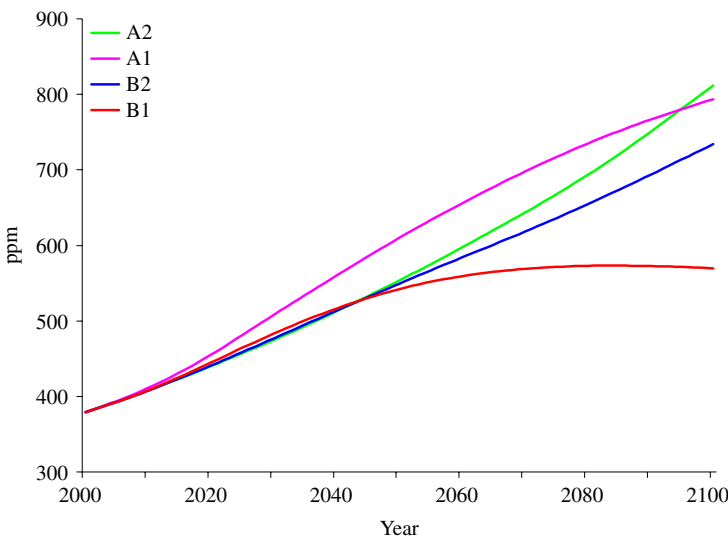
Figure 4. The atmospheric concentration of carbon dioxide according to the four SRES marker scenarios, as implemented in FUND.
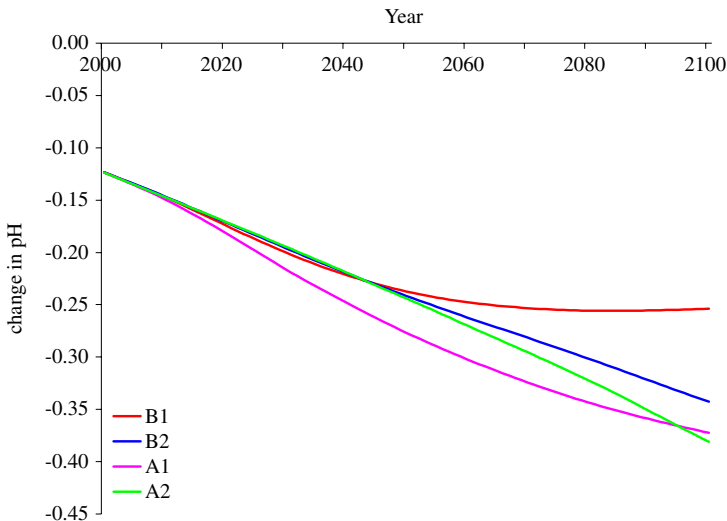
Figure 5. The change in ocean acidity according to the four SRES marker scenarios, as implemented in FUND and Eq. (1).
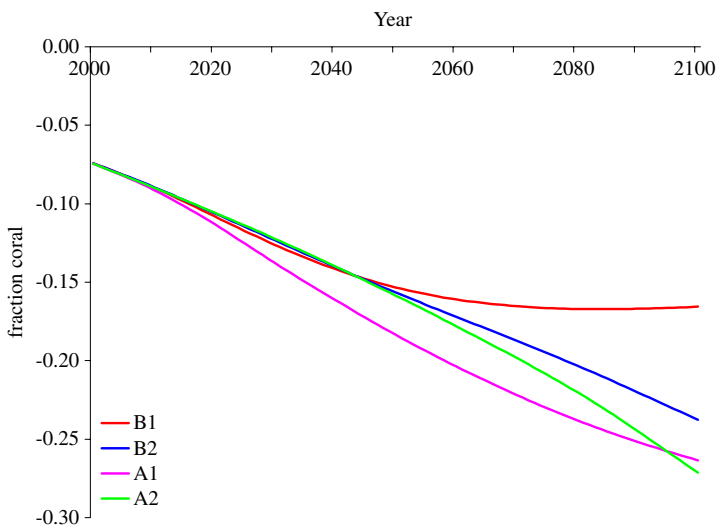
Figure 6. The change in coral reef area according to the four SRES marker scenarios, as implemented in FUND and Eq. (2).

ocean acidification. The loss in 2100 ranges from 16% or 30,000 km^2 (but falling[4]) in B1 to 27% or 65,000 km^2 (and accelerating) in A2. Again, this pattern follows straightforwardly from the pH values in Fig. 4. It should be noted that the estimated loss in coral area is only due to projected ocean acidification and not to other

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[4]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.
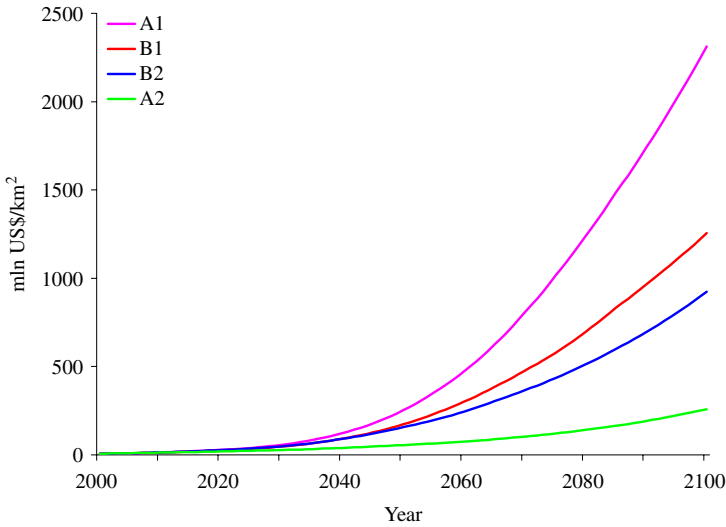
Figure 7. The unit value of coral reefs according to the four SRES marker scenarios, as implemented in FUND and the meta-regression.

factors that may result in coral degradation (e.g., warming, sea level rise, pollution, mining etc.).

Figure 7 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.[5] Several variables feed into the meta-regression (cf. Sec. 3). Population density and per capita income are part of the SRES scenarios. We assumed that the growth rates for population and income are uniform across the countries in the FUND regions,[6] and used these growth rates to extrapolate the national coral reef value. The number of visitors is also important (Table 2). We used the number of international arrivals according to the Hamburg Tourism Model (Hamilton *et al.*, 2005). See Fig. A1 in the Appendix. Coral reef area also affects coral reef value. We used the areal change of Fig. 6. 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 km^2, 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, so that there are more people to appreciate coral reefs. Secondly, coral reef area falls substantially,

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[5]Using the ReefBase database: http://www.reefbase.org/global_database/default.aspx
[6]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/.
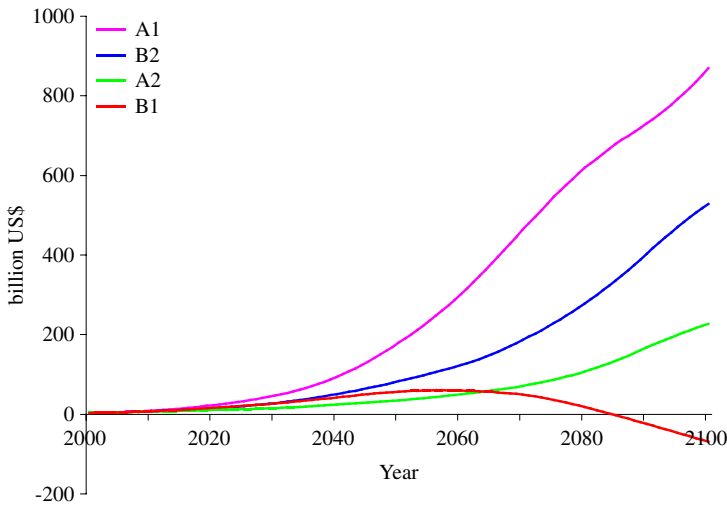
Figure 8.   The annual economic damage of ocean-acidification-induced coral reef area loss.

so that the scarcity value of the remaining area increases. These two factors contribute relatively little, because the elasticities are relatively small (around 0.5). The third development is more important. Visitor 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: As people grow richer, the money value they attach to coral reefs grows fast.

Figure 8 shows the *annual* economic damage of ocean-acidification-induced coral reef loss. Figure 8 multiplies Fig. 6 (area loss) and Fig. 7 (net present value per area),[7] and expresses the result as a fraction of GDP. Damages are higher in the A1 and B2 scenarios than in the A2 scenario because coral values are higher in A1 and B2 than in A2. The B2 scenario has both lower values and lower losses 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 US\$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).

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[7]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.
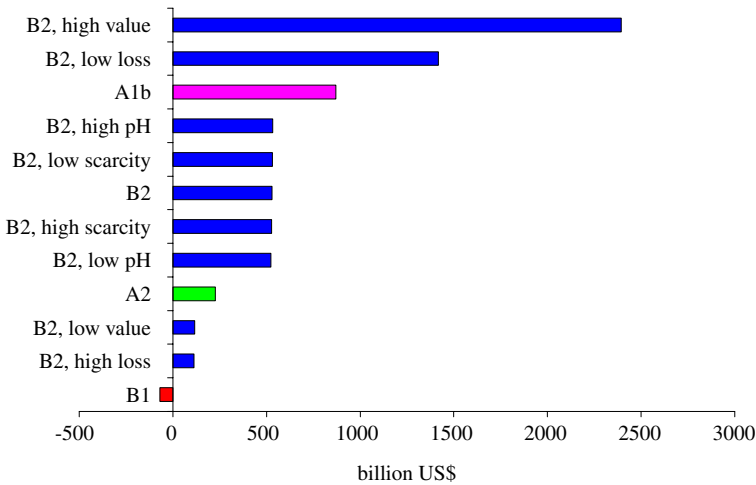
Figure 9. A sensitivity analysis around the annual economic damage of ocean-acidification-induced coral reef area loss.

Figure 9 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. For comparison, the results of the other three scenarios are also shown. Parameters were varied by one standard deviation including the parameters describing the relationship between ocean surface acidity and atmospheric concentration (low and high pH), area of coral cover (low and high scarcity), reef area lost (low and high loss), and value of reef area (low and high value).

The response of ocean acidity to ambient carbon dioxide concentrations is not particularly uncertain, and damages are hardly affected. In the base case, the damage in 2100 is $528 billion. The error around this relationship increases or decreases damages by $2 billion. The area elasticity of value is not that important either: Damages go up or down by $5 billion. The choice of scenario make a substantial difference: Under the B1 scenario, there is a positive impact of $69 billion; this is $228 billion for A2, $528 billion for B2 and $870 for A1b. 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 damage ranges from $112 to $1,417 billion. The largest uncertainty, more than a factor four, is the value per unit area. The range of damages is from $117 to $2,293 billion.

5. Discussion and Conclusion

This paper gives one of the first partial estimates of the economic value of ocean acidification. This estimate is limited to the impact on coral reefs, perhaps the most tractable of the many 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. We drive this by CO_2 emissions, population, and income 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 recreational activities related to 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). This is not surprising since we estimated only the economic impact of ocean acidification on coral reefs where recreation has a dominant role and did not look at any other impacts. 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; to explore the distribution of impacts and vulnerability of impacted populations; and to investigate the interactions between ocean acidification, climate change, and sea level rise.

Acknowledgements

Appendix

Table A1. Economic valuation studies used in the meta-analysis.

Author(s)	Date	Title	Publication
Andersson	2003	The recreational cost of coral bleaching: A stated preference study of international tourists	Paper presented at the 2003 EAERE conference in Bilbao
Arin	1998	Estimating the tourist demand for international dive vacations: A pretest	Master of Science Thesis, Nicholas School of the Environment, Duke University
Ayob *et al.*	2000	Preferences for outdoor recreation: The case of Pulau Payar visitors	Paper presented at the First Conference of the Malaysian Association for Resource and Environmental Economics
Brown *et al.*	2000	Trade-off analysis for marine protected area management	CSERGE Working Paper, University of East Anglia, UK
Bappenas	1996	Recreation values of tourists for Bunaken National Marine Park, North Sulawesi	Indonesian Ministry of Forestry Report No. 66
Berg *et al.*	1998	Environmental economics of coral reef destruction in Sri Lanka	Ambio
Bowker and Leeworthy	1998	Accounting for ethnicity in recreation demand: A flexible count data approach	*Journal of Leisure Research*
Brock	1994	Beyond fisheries enhancement: Artificial reefs and ecotourism	Bulletin of Marine Science
Carr and Mendelsohn	2001	Valuing coral reefs: A travel cost analysis of the Great Barrier Reef	Yale School of Forestry and Environmental Studies
Cesar and van Beukering	2004	Economic valuation of the coral reefs of Hawaii	Pacific Science
Cesar *et al.*	2003	Mainstreaming economic valuation in decision making: Coral reef examples in selected CARIDOM countries	ARCADIS-Euroconsult
Cesar and van Beukering	2002	Economic valuation of the coral reefs of Hawaii	Hawaii Coral Reef Initiative Research Program
Cesar	1996	Economic analysis of indonesian coral reefs	World Bank
Driml	1999	Dollar values and trends of major direct uses of the Great Barrier Reef Marine Park	Great Barrier Reef Marine Park Authority
Driml	1994	Protection for profit: Economic and financial values of the great barrier reef world heritage area and other protected areas	Great Barrier Reef Marine Park Authority

Table A1. (*Continued*)

Author(s)	Date	Title	Publication
Davis and Tisdell	1996	Economic management of recreational scuba diving and the environment	*Journal of Environmental Management*
Dixon	1993	Economic benefits of marine protected areas	Oceanus
Dixon *et al.*	1993	Meeting ecological and economic goals: The case of marine parks in the caribbean	World Bank
Edwards	1991	The demand for Galapagos vacations: Estimation and application to wilderness preservation	Coastal Management
English *et al.*	1996	Economic contribution of recreation visitors to the Florida Keys/Key West	National Oceanographic and Atmospheric Adminstration
GEF/UNDP/IMO	1999	Total economic valuation: Coastal and marine resources in the Straits of Malacca	Global Environment Facility
Hodgson and Dixon	1988	Logging versus fisheries and tourism in Palawan	East-West Center
Johns *et al.*	2001	Socioeconomic study of reefs in Southeast Florida (executive summary)	National Oceanographic and Atmospheric Adminstration
KPMG Consulting	2000	Economic and financial values of the Great Barrier Reef Marine Park	Great Barrier Reef Marine Park Authority
Kragt *et al.*	2006	Recreational demand under Great Barrier Reef degradation: A contingent behaviour approach	FEEM Working Paper No. 45.2006
Leeworthy and Wiley	1996	Importance and satisfaction ratings by recreating visitors to the Florida Keys/Key West	National Oceanographic and Atmospheric Adminstration
Leeworthy *et al.*	1997	Nonmarket economic user values of the Florida Keys/Key West	National Oceanographic and Atmospheric Adminstration
Lindberg	1993	An analysis of ecotourism's economic contribution to conservation and development in Belize	Griffith University, Australia
Mak and Moncur	1998	Political Economy of protecting unique recreational resources: Hanauma Bay, Hawaii	Ambio
Ngazy	2004	Recreational coral bleaching and the demand for coral reefs: A case study	International Centre for Living Aquatic Resources Management

Table A1. (*Continued*)

Author(s)	Date	Title	Publication
Peachy	1998	An economic analysis of water based recreation in the Great Barrier Reef Marine Park	Great Barrier Reef Marine Park Authority
Pendleton	1995	Valuing coral reef protection	Ocean and Coastal Management
Pham and Tran	2001	Analysis of the recreational value of the coral-surrounded Hon Mun Islands in Vietnam	EEPSEA report
Riopelle	1995	The economic valuation of coral reefs: A case study of West Lombok, Indonesia	Dalhousie University, Canada
Ruitenbeek *et al.*	1999	Optimization of economic policies and investment projects using a fuzzy logic based cost-effectiveness model of coral reef quality: Empirical results for Montego Bay, Jamaica	Coral Reefs
Sudara *et al.*	1991	Tourism for economic gain in the vicinity of Samui and Pha-ngan Islands	
Seenprachawong	2003	Economic valuation of coral reefs at Phi Phi Islands, Thailand	Proceedings of the Regional Symposium on Living Resources in Coastal Areas. Marine Science Institute, University of the Philippines
Setiasih	2000	Recreational valuation using contingent and conjoint analysis: A study from Menjangan Island, Bali Barat National Park	University of East Anglia, UK
Tabata and Reynolds	1995	Hawaii's recreational dive industry: Results and recommendations of a 1990 study	
Vogt	1997	The economic benefits of tourism in the marine reserve of Apo Island, Philippines	Proceedings of the 8th International Coral Reef Symposium, Panama
Weber *et al.*	1996	Managing a coral reef ecosystem in Indonesia	Paper presented to the 4th Biennial Meeting of the International Society for Ecological Economics, Boston, Massachusetts, USA

Table A1.   (*Continued*)

Author(s)	Date	Title	Publication
Wiley	1999	A cost-benefit analysis for a proposed wastewater treatment plant in the Florida Keys	National Oceanographic and Atmospheric Adminstration
White *et al.*	1997	Using integrated coastal management and economics to conserve coastal tourism resources in Sri Lanka	Ambio
White *et al.*	2000	Benefits and costs of coral reef and wetland management, Olango Island, Philippines	Cordio
Yeo	2004	The recreational benefits of coral reefs: A case study of Pulau Payar Marine Park	International Centre for Living Aquatic Resources Management

Table A2. Descriptive statistics for the variables in the meta-regression (cf. Table 2).

Variable	Definition	Mean	Standard Deviation
Dependent variable			
Coral reef value	US\$ per km^2 per year (ln)	10.946	2.392
Socio-economic			
GDP per capita	GDP per capita (ln)	9.141	1.275
Population density	Population density 50 km radius (ln)	3.924	1.374
Visitors	Number of visitors (ln)	11.514	2.312
Location			
USA	1 = USA; 0 = other	0.366	0.485
East Africa	1 = East Africa; 0 = other	0.110	0.315
Southeast Asia	1 = Southeast Asia; 0 = other	0.256	0.439
Australia	1 = Australia; 0 = other	0.098	0.299
Caribbean	1 = Caribbean; 0 = other	0.169	0.376
Reef quality			
Area coral cover	Area coral cover km^2 (ln)	3.902	2.703
Biodiversity index	Biodiversity index (ln)	−1.290	0.773
Services			
Dive tourism	1 = Diving; 0 = other	0.720	0.452
Snorkeling	1 = Snorkeling; 0 = other	0.561	0.499
Other reef tourism	1 = Tourism; 0 = other	0.451	0.501
Commercial fishing	1 = Commerical fishing; 0 = other	0.073	0.262
Recreational fishing	1 = Recreational fishing; 0 = other	0.012	0.110
Coastal protection	1 = Coastal protection; 0 = other	0.024	0.155
Biodiversity	1 = Biodiversity; 0 = other	0.012	0.110
Preservation	1 = Preservation; 0 = other	0.061	0.241
Valuation method			
CVM	1 = CVM; 0 = other	0.488	0.503
Travel cost method	1 = Travel cost; 0 = other	0.134	0.343
Net factor income	1 = NFI; 0 = other	0.085	0.281
Production function	1 = Production function; 0 = other	0.073	0.262
Gross revenue	1 = Gross revenue; 0 = other	0.207	0.408

Table A3. Selected characteristics of affected countries: Reef area in 2000; population, per capita income, international tourist arrivals in 2000 and assumed growth rates for the 21st century.

	Reef km²	Population	Population growth rate (%)				Income billion US$	Income growth rate (%)				Arrivals	Arrivals growth rate (%)			
			A1	A2	B1	B2		A1	A2	B1	B2		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

Table A3. (Continued)

	Reef km²	Population	Population growth rate (%)				Income billion US$	Income growth rate (%)				Arrivals	Arrivals growth rate (%)			
			A1	A2	B1	B2		A1	A2	B1	B2		A1	A2	B1	B2
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
Vietnam	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
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

Table A3. (*Continued*)

	Reef km^2	Population	Population growth rate (%)				Income billion US$	Income growth rate (%)				Arrivals	Arrivals growth rate (%)			
			A1	A2	B1	B2		A1	A2	B1	B2		A1	A2	B1	B2
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 and 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

Table A3. (*Continued*)

|	Reef km²	Population	Population growth rate (%)				Income billion US$	Income growth rate (%)				Arrivals	Arrivals growth rate (%)			
			A1	A2	B1	B2		A1	A2	B1	B2		A1	A2	B1	B2
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
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
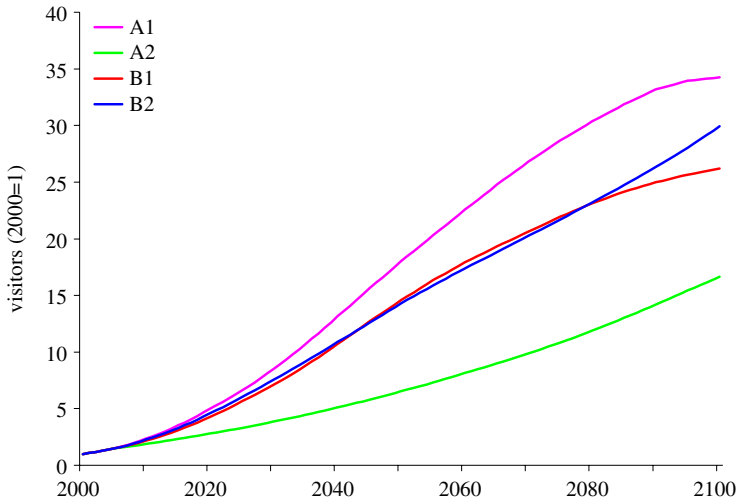
Figure A1. International visitors to coral reefs according to the four SRES marker scenarios, as implemented in FUND and HTM.

References

Andersson, AJ, NR Bates and FT 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, AJ, FT MacKenzie and LM Ver (2003). Solution of shallow-water carbonates: An insignificant buffer against rising atmospheric CO$_2$. *Geology*, 31(6), 513–516.

Anthony, KR, JA Kleypas, J-P Gattuso (2011). Coral reefs modify their seawater carbon chemistry — implications for impacts of ocean acidification. *Global Change Biology*, 17, 3655–3666.

Bateman, I and LP Jones (2003). Contrasting conventional with multi-level modeling approaches to meta-analysis: Expectation consistency in U.K. woodland recreation values. *Land Economics*, 79(2), 235–258.

Brander, LM, JGM Florax and JE Vermaat (2006). The empirics of wetland valuation: A comprehensive summary and meta-analysis of the literature. *Environmental and Resource Economics*, 33(2), 223–250.

Brander, LM, PJH van Beukering and HSJ Cesar (2007). The recreational value of coral reefs: A meta-analysis. *Ecological Economics*, 63, 209–218.

Brouwer, R, IH Langford, IJ Bateman, TC Crowards and RK Turner (1999). A meta-analysis of wetland contingent valuation studies. *Regional Environmental Change*, 1, 47–57.

Brouwer, R (2000). Environmental value transfer: State of the art and future prospects. *Ecological Economics*, 32, 137–152.

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

Caldeira, K and ME 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 AK Jain (2007). Effects of carbon dioxide and climate change on ocean acidification and carbonate mineral saturation. *Geophysical Research Letters*, 34(L05607), 1–5.

Carson, RT, NE Flores, KM Martin and JL Wright (1996). Contingent valuation and revealed preference methodologies: Comparing the estimates for quasi-public goods. *Land Economics*, 72, (Feb), 80–99.

Castles, I and D Henderson (2003). The IPCC emission scenarios: An economic-statistical critique. *Energy and Environment*, 14(2–3), 159–185.

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

Cesar, HSJ, P van Beukering and RG de Berdt (2003b). *Mainstreaming Economic Valuation in Decision Making*: *Coral Reef Examples in Selected CARIDOM-Countries*, Cesar Environmental Economic Consulting, Arnhem.

Cooley, SR and SC Doney (2009). Anticipating ocean acidification' seconomic consequences for commercial fisheries. *Environmental Research Letters*, 4, doi:10.1088/1748-9326/4/2/024007.

Cooley, SR, L Lucey, H Kite-Powerll and SC Doney (2011). Nutrition and income from molluscs today imply vulnerability to ocean acidification tomorrow. *Fish and Fisheries* (published online, DOI: 10.1111/j.1467-2979.2011.00424.x).

d'Arge, R, WD Schulze and DS Brookshire (1982). Carbon dioxide on intergenerational choice. *American Economic Review*, 72(2), 251–256.

Freeman III, AM (2003). *The Measurement of Environmental and Resource Values*: *Theories and Methods*, Resources for the Future, Washington D.C.

Gattuso, J-P, M Frankignoulle, I Bourge, S Romaine and RW Buddemeier (1998). Effect of calcium carbonate saturation of seawater on coral calcification. *Global and Planetary Change*, 18, 37–46.

Gazeau, F, C Quiblier, JM Jansen, J-P Gattuso, JJ Middelburg and CHR Heip (2007). Impact of elevated CO_2 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, JM, R Rodolfo-Metalpa, S Martin, E Ransome, M Fine, SM Turner, SJ Rowley, D Tedesco and M-C Buia (2008). Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. *Nature*, 454, 96–99.

Hamilton, JM, DJ Maddison and RSJ 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, PJ Mumby, AJ Hooten, RS Steneck, P Greenfield, E Gomez, CD Harvell, PF Sale, AJ Edwards, K Caldeira, N Knowlton, CM Eakin, R Iglesias-Prieto, N Muthiga, RH Bradbury, A Dubi and ME Hatziolos (2007). Coral reefs under rapid climate change and ocean acidification. *Science*, 318, 1737–1742.

Key, RM, A Kozyr, CL Sabine, K Lee, R Wanninkhof, JL Bullister, RA Feely, FJ Millero, C Mordy and TH Peng (29-12-2004). A global ocean carbon climatology: Results from global data analysis project (GLODAP). *Global Biogeochem Cycles*, 18.

Kleypas, JA, RW Buddemeier, D Archer, J-P Gattuso, C Langdon and BN Opdyke (1999). Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. *Science*, 284, 118–120.

Kleypas, JA, KRN Anthony and J-P Gattuso (2011). Coral reefs modify their seawater carbon chemistry — case study from a barrier reef (Moorea, French Polynesia). *Global Change Biology*, 17, 3667–3678.

Kopp, RJ and VK Smith (eds.) (1993). *Valuing Natural Assets, the Economics of Natural Resource Damage Assessment*, Resources for the Future, Washington, D.C.

Langdon, C, T Takahashi, C Sweeney, D Chipman, J Goddard, F Marubini, H Aceves, H Barnett and MJ 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, BI and RJ Matear (2006). Projected climate change impact on oceanic acidification. *Carbon Balance and Management*, 1(2), 1–6.

McNeil, BI and RJ Matear (2007). Climate change feedbacks on future oceanic acidification. *Tellus*, 59B, 191–198.

Morse, JW, AJ Andersson and FT MacKenzie (2006). Initial responses of carbonate-rise shelf sediments to rising atmospheric $p$$CO_2$ and ocean acidification: Role of High Mg-Calcites. *Geochimica et Cosmochimica Acta*, 70, 5814–5830.

Munday, PL, NE Crawley and GE Nilsson (2009). Interacting effects of elevated temperature and ocean acidification on aerobic performance in coral reef fishes. *Marine Ecology Progress Series*, 388, 235–242.

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

Narita, D, K Rehdanz and RSJ Tol (2012). 'Economic costs of ocean acidification: A look into the impacts on shellfish production'. Climate Change, DOI:10.1007/S10584-011-0383-3.

Nordhaus, WD (1991). To slow or not to slow: The economics of the greenhouse effect. *Economic Journal*, 101, 920–937.

Orr, JC, VJ Fabry, O Aumont, L Bopp, SC Doney, RA Feely, A Gnanadesikan, N Gruber, A Ishida, F Joos, RM Key, K Lindsay, E Maier-Reimer, R Matear, P Monfray, A Mouchet, RG Najjar, G-K Plattner, KB Rodgers, CL Sabine, JL Sarmiento, R Schlitzer, RD Slater, IJ 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, RA, Jr, TML Wigley and C Green (2008). Dangerous assumptions. *Nature*, 452, 531–532.

Ridgwell, A, I Zondervan, JC Hargreaves, J Bijma and TM 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, PD Tortell, RE Zeebe and FMM Morel (2000). Reduced calcification of marine plankton in response to increased atmospheric CO_2. *Nature*, 407, 364–367.

Royal Society (2009). Geoengineering the climate: Science, governance and uncertainty, The Royal Society, UK, http://royalsociety.org/geoengineering-the-climate/.

Schelling, TC (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.

Smith, VK and K Pattanayak (2002). Is meta-analysis a Noah's ark for non-market valuation?. *Environmental and Resource Economics*, 22, 271–96.

Spicer, JI, 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.

Stanley, TD (2001). Wheat from Chaff: Meta-analysis as quantitative literature review. *Journal of Economic Perspectives*, 15, 131–150.

Tol, RSJ (2005). The marginal damage costs of carbon dioxide emissions: An assessment of the uncertainties. *Energy Policy*, 33, 2064–2074.

Tol, RSJ (2008a). Climate, development and malaria: An application of FUND. *Climatic Change*, 88(1), 21–34.

Tol, RSJ (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.

Veron, JEN, OL Hoegh–Guldberg, TM Lough d, JM Obura, DO Pearce-Kelly, P Sheppard, CRC Spalding, M Stafford-Smith, MG?, AD Rogers (2009). The coral reef crisis: The critical importance of <350 ppm CO_2. *Marine Pollution Bulletin*, 58, 1428–1436.

Veron, JEN (2011). Ocean acidification and coral reefs: An emerging big picture. *Diversity*, 3, 262–274; doi:10.3390/d3020262.

Wagtendonk, A and N Omtzigt (2003). Analysis of population density around wetland areas in GPW (Gridded population of the world) files. Amsterdam: SPINlab document, Institute for Environmental Studies, VU University Amsterdam.

Westmacott, S, HSJ 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*, Cesar, HSJ (ed.), Kalmar University, Kalmar.

Wilkinson, C, O Linden, HSJ Cesar, GM Hodgson, J Rubens and AE 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.

Woodward, RT and Y-S Wui (2001). The economic value of wetland services: A meta-analysis. *Ecological Economics*, 37, 257–70.

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.