

# The economic impacts of ocean acidification

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## Abstract

Ocean acidification caused by the increased uptake of atmospheric carbon dioxide by the oceans is likely to have serious impacts on marine organisms that make shells and exoskeletons from calcium carbonate. The consequences for the provision of marine ecosystem services such as fisheries and services generated by coral reefs are uncertain but potentially severe. In this chapter we set out a framework for the economic assessment of impacts from ocean acidification. We review the existing economic literature on ocean acidification, which is nascent and sparse. To date only a partial set of the potentially impacted ecosystem services have been assessed with a focus on the direct use values that can be more easily addressed. Gaps in the current knowledge are identified and avenues for future research are discussed. Comparing the existing impact estimates for ocean acidification with those for climate change show them to be an order of magnitude lower. Due to the relatively proximate impacts of ocean acidification, however, the implications for optimal mitigation of carbon dioxide emissions may be substantial.

*Keywords:* ocean acidification; economic impacts.

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## 1. Introduction

Carbon dioxide dissolves in sea water to form carbonic acid. As the atmospheric concentration of carbon dioxide increases, so does the oceanic concentration in order to maintain the chemical equilibrium between seawater and the atmosphere. Carbon emissions from fossil fuel combustion and land use change thus makes ocean water more acidic.<sup>1</sup>

Ocean acidification reduces the availability of calcium carbonate in the oceans. When carbon dioxide bonds with sea water to form carbonic acid, a bicarbonate ion and hydrogen ion are released. The free hydrogen ions then bond with free carbonate ions and thereby reduce the availability of carbonate ions for marine animals that make calcium carbonate shells and skeletons. Ocean acidification therefore spells potential trouble for species with an exoskeleton. Shellfish and corals spring immediately to mind, but many micro-organisms in the ocean crucially depend on calcium carbonate as well. Besides the direct impact on vulnerable species, ocean acidification also affects the food chain for animals in the oceans and elsewhere.

This affects humans too. Fisheries and aquaculture are an important source of income and food, particularly proteins. Coral reefs protect coasts from storm damage and erosion, supply sediments to form beaches and support the livelihoods of entire small island nations. Coral reefs harbour valuable fish and provide excellent opportunities for recreation. Marine species make up a major part of global biodiversity, and play a role in the global carbon cycle. Prima facie, ocean acidification is a reason for concern.

However, despite their great importance, the services provided by marine and coastal ecosystems have received far less attention than those provided by terrestrial ecosystems – possibly due to the difference in access and direct experience (TEEB, 2009). The same is true for the economic impact of ocean acidification. This chapter reviews the available literature on this issue, which is nascent and sparse.

Economic impact estimates of ocean acidification are needed for a number of reasons. Ocean acidification is an externality of carbon dioxide emission, presumably negative, that requires correcting. Damage cost estimates are required in order to determine the optimal level of mitigation. In the likely case that mitigation is insufficient and delayed, and that atmospheric concentrations of carbon dioxide continue to increase over the next century, there is a need for impact estimates to guide adaptation efforts. Adaptation options that reduce the local biogeochemical impacts of ocean

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<sup>1</sup> Seawater is historically slightly alkaline with a global mean of approximately pH 8.6. Ocean acidification describes a relative decrease in seawater pH toward acidity but it is not expected that seawater pH will reach the acid side of the scale.

acidification may be limited (e.g. spreading pulverized olivine or calcium hydroxide) and so adaptation is limited to replacing impacted ecosystem services and finding alternative sources of food and livelihood.

Ocean acidification is different from, but related to, climate change. Climate change is caused by a range of greenhouse gases, whereas ocean acidification is caused by carbon dioxide only (and has been described as “the other CO<sub>2</sub> problem”). Climate engineering is a possible solution for climate change, but not necessarily for ocean acidification. In fact, ocean acidification may accelerate if sulphur particles (which acidify too) are used to deflect sunlight. Climate change is slow because of the slow uptake of energy by the ocean whereas ocean acidification is expected to occur more rapidly. Ocean acidification is therefore not just an extra reason to reduce carbon dioxide emissions but has qualitative impacts on optimal mitigation policy. In addition, a potential feedback effect between ocean acidification and climate change is possible. Ocean acidification is likely to result in a decline in the rate at which the oceans absorb carbon dioxide since less carbon is stored in calcium carbonate shells and skeletons. This means that a greater proportion of carbon dioxide emissions remains in the atmosphere and exacerbates climate change.

The chapter continues as follows. Section 2 presents the framework for assessment. Section 3 discusses the available estimates. Section 4 reviews the gaps in knowledge. Section 5 concludes.

## **2. Framework for assessing the economic impacts of OA**

The assessment of the economic impacts of ocean acidification requires the linking of biophysical processes with human benefits derived from the marine environment. This link can usefully be made through the concept of ecosystem services (TEEB, 2010). Ecosystem services can be defined as the outputs of ecosystems from which people derive benefits (UK NEA, 2011). Ecosystem services can either be “final” goods and services that people benefit from (e.g., coastal protection, non-use biodiversity values) or be used as inputs in the production of “final” goods and services (e.g. wild caught and aquaculture fish). It is the value of “final” goods and services that need to be quantified in an economic assessment of ecological impacts. Applying the concept of ecosystem services is useful in making a distinction between ecosystem functions (processes) and benefits to humans, and ensures that assessments of ecological impacts are more accessible to economic valuation. Any ecosystem assessment still needs to determine the change in service provision in biophysical terms to give a solid ecological basis to the economic valuation (TEEB, 2010).

The assessment of the impacts of ocean acidification on economic welfare requires that the full impact pathway is understood and modelled. This demands the coupling or integration of models that explain

each step in the pathway linking (1) socio-economic activities, CO<sub>2</sub> emissions, ocean acidification, (2) impacts on marine ecosystems, (3) changes in the provision of ecosystem services, and finally (4) impacts on human welfare (see Figure 1). Each of these components in themselves are complex research topics that are characterised by varying degrees of scientific understanding and uncertainty.

The biogeochemistry (1) of increasing atmospheric concentrations of CO<sub>2</sub>, uptake of CO<sub>2</sub> by the oceans, resulting a decrease in seawater pH and availability of calcium carbonate is relatively well understood, albeit with spatial variation depending on physical determinants of CO<sub>2</sub> solubility such as depth, temperature and circulation (Doney et al., 2009).

The impacts of ocean acidification (2) on individual species and marine ecosystems are now the subject of considerable research attention. For a comprehensive review see Gattuso and Hansson (2011). In general the impacts are still not well understood, particularly as the focus moves from individual species that are directly impacted by calcium carbonate availability (e.g. mollusks and reef building corals) to species that are more distant in the food web (e.g. commercially important fish species and “charismatic” mammals) and to the impact of multiple stressors on the marine environment (e.g. temperature change, pollution, over fishing).

The next step (3) in the impact pathway, namely the change in provision of ecosystem services, is still less well understood and also less well studied. Although potential impacts on commercial mollusk and fish harvests have been addressed in a number of studies, there remains no modelled or empirical quantification of the effect of species level biophysical changes on harvests. As yet there has been little research on the impacts of ocean acidification on the provision of ecosystem services from coral reefs (e.g. recreational opportunities, beach formation, coastal protection, and non-use values for biodiversity).

The estimation of economic welfare impacts (4) of changes in the provision of ecosystem services requires information on the value of these services and how values change with the level of provision. It is important to note that changes in the value of marine ecosystem services are determined by changes in both supply and demand, the latter being determined by the characteristics of the beneficiaries that receive those services (population, income, preferences etc.). It is therefore necessary to also account for changes in demand for marine ecosystem services over the course of the time frame of ocean acidification impacts (i.e. the populations that will be impacted will be very different from the present). This point is indicated by the arrow at the top of Figure 1. The valuation of ecosystem services from the marine environment is further complicated by the fact that some services are not traded, directly or indirectly, in markets and therefore do not have market prices (e.g. coastal protection provided by coral reefs and non-use biodiversity values). The valuation and

distribution of economic impacts has received little research attention and we review the few existing studies in the following section.

It is important to note that the linkages between each component step in the ocean acidification impact pathway are perhaps still less well understood since they fall between disciplines. The assessment of OA impacts therefore requires an integration of research findings that bridges disciplinary boundaries, which involves challenges of information compatibility and communication.

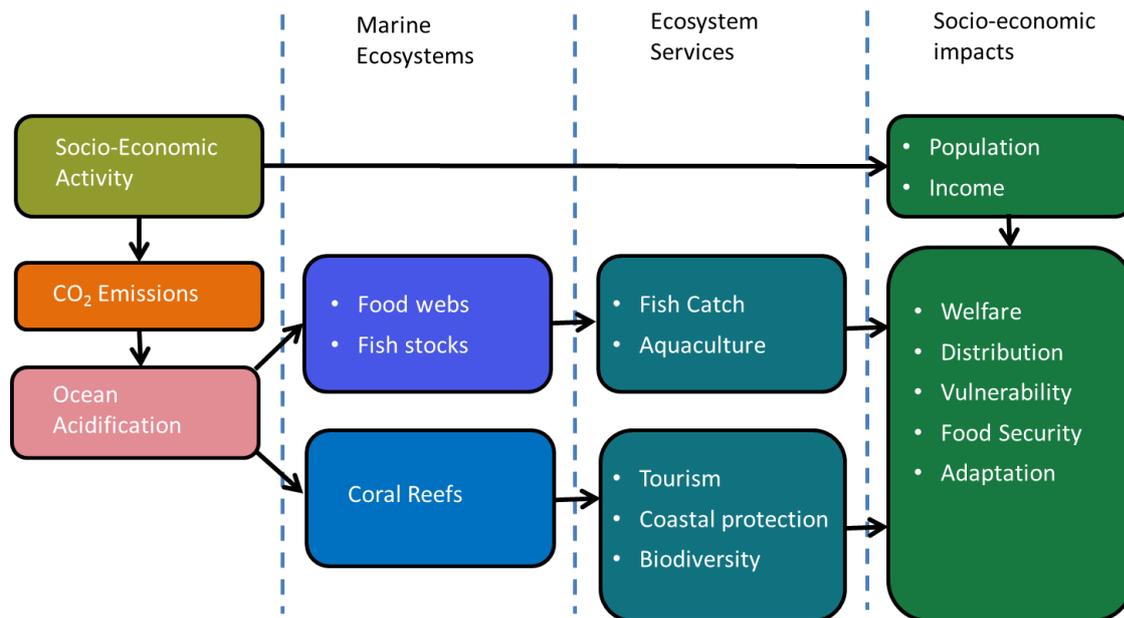


Figure 1. Impact pathway for ocean acidification

### 3. The current evidence on economic impacts of ocean acidification

Despite the potentially severe impacts of ocean acidification on marine ecosystem services, there has been relatively little research on the economic costs involved. In this section we summarise and review the existing literature that addresses the economic impacts of ocean acidification. The purpose of this review is to take stock of the current understanding of this issue, the methods employed, the ecosystem services addressed and the geographic scope of analysis. Summary information for each study is presented in Table 1.

Kite-Powell (2009) provides a discussion of the main economic impacts of acidification, namely to fisheries and the ecosystem services provided by coral reefs. The paper gives rough estimates of the total value of these ecosystem services (in gross revenue terms) but argues that currently available knowledge and models are not sufficient to quantify the impacts of ocean acidification with any

certainty. The point is made that the adaptive response of marine ecosystems and humans to ocean acidification is not known.

Finnoff (2010) sets out the economic approach to valuing the impacts of ocean acidification on the provisioning of ecosystem services. The paper argues that the welfare implications of ocean acidification need to be measured in terms of changes in consumer and producer surplus rather than changes in gross revenues (as is done in a number of studies). Finnoff makes the point that the standard economic framework for assessing material damages, such as the degradation of an environmental input into production or consumption, has been available for some time but that the implementation remains challenging. A particular challenge is the integration of highly complex ecological processes into economic models. On one hand, the use of a reduced form representation of the natural system may be overly simplified and miss non-convexities in the ecological system. On the other hand, the use of detailed structural models may better capture the complexities of the system but become intractable. Using an existing model of the Bering Sea ecosystem, the paper provides a simulation of ocean acidification impacts in order to highlight the complexities of assessing impacts in systems characterised by non-convexities. The paper does not attempt to estimate values for ocean acidification impacts.

Brander et al. (2012) provide a first estimate of the global economic impact of ocean acidification on coral reefs. The paper constructs and calibrates simple models of ocean acidification and coral reef area loss, driven by the atmospheric concentration of carbon dioxide. Carbon dioxide emissions and concentrations are modelled for the four SRES (Special Report on Emissions Scenarios) scenarios using the FUND (Climate Framework for Uncertainty, Negotiation and Distribution) integrated assessment model. A meta-analysis of coral reef values is used to estimate a value transfer function for coral reef ecosystem services. An existing model of tourist numbers is applied to estimate future visitor numbers to coral reef locations. Combining these models, the annual value of lost ecosystem services due to ocean acidification induced coral reef loss is estimated. The economic value of lost coral reef ecosystem services varies across scenarios due to (1) differing rates of CO<sub>2</sub> emissions, ocean acidification and loss of coral cover; (2) differing rates of population and income growth that determine the value of coral reef services per unit area of coral cover. The results show that the annual economic impact (loss of coral reef service value) escalates rapidly over time, essentially because the scenarios have high economic growth in countries with coral reefs and because demand for coral reef services increases more than proportionately with income. Nonetheless, the annual value of foregone ecosystem services from coral reefs in 2100 is still only estimated to be a small fraction of total global income (0.14% or US\$ 870 billion in 2100; 2000 price levels; SRES scenario A1B). The estimated impacts are, however, considered to be partial since the underlying value data is largely focussed on recreational values and includes limited information on the value of other services such as coastal

protection or non-use values for biodiversity. The study reports the results of a sensitivity analysis and shows that the estimated impact is highly uncertain, with a confidence interval spanning one order of magnitude. It is important to note that other threats to the health of coral reefs and the provision of reef services are not included in this analysis (e.g. over fishing, sedimentation, eutrophication, sea level and temperature rise). The impact of ocean acidification on coral reef services may therefore be overstated in the case that coral reefs are more rapidly degraded by the combined stress of multiple threats. The projection of coral reef functioning under combined stressors adds a considerable degree of complexity, as does the attribution of coral reef damage to specific stressors.

Cooley and Doney (2009) estimate the impact of ocean acidification on gross revenues for US mollusk fisheries up to 2060. They combine experiment level information on the impact of ocean acidification on growth rates of mollusks with data on US fisheries harvests and prices. Baseline future revenues are projected to 2060 assuming no changes in ecological and economic conditions prevailing in 2007 (i.e., catch, prices and revenues remain constant). Under an ocean acidification scenario, the time profile of increasing impacts on mollusk growth is assumed to be linear and proportionately related to revenue for the period 2007-2060. The estimated present value of losses in revenue are shown to be sensitive to CO<sub>2</sub> emission trajectories, impacts on mollusk growth and the discount rate used in calculating present values. Under the IPCC A1F1 scenario, the present value of lost revenue is estimated to be US\$ 2,557 million (25% reduction in mollusk growth at 740 ppm CO<sub>2</sub>; 2% discount rate).

Narita et al (2012) estimate the value of global and regional loss of mollusk production due to ocean acidification over the period 2000-2100. A partial-equilibrium analysis is used to quantify both producer and consumer surplus and accounts for two determinants of welfare change, namely reduced production/consumption and increased prices. Following Cooley and Doney (2009), the rate of shellfish harvest loss is assumed to be equal to the decrease in calcification rate due to ocean acidification. Narita et al (2012) use an estimate of the decrease in calcification rate from a different meta-study (Kroeker et al., 2010), which is higher than that used by Cooley and Doney (2009). The results show that the annual global costs in 2100 could be over 100 billion US\$ under a business-as-usual emission trend and assuming that demand for mollusks increases with income, the trend for which is based on the IPCC projections. The major determinants of this cost estimate are the impacts on Chinese production, which is projected to dominate global production, and the expected increase in demand for mollusks in developing countries, including China, in accordance with future income rise. The analysis also indicates that in key regions such as China and the USA, the economic losses are roughly evenly divided between producers and consumers, with slightly greater relative consumer losses for China as a result of relatively inelastic demand of mollusks in that country.

Moore (2011) develops an integrated biogeochemical-economic model to estimate the potential impacts of ocean acidification on the US market for oysters, scallops, clams, and mussels for the period 2010-2100. The welfare measure that is estimated is the compensating variation of US households. Compensating variation reflects the change in consumer welfare following a change in prices and is defined as the amount of additional income that a household would need in order to obtain their original level of utility prior to a price increase. The estimated impact therefore represents the loss in consumer welfare due to increased mollusk prices caused by ocean acidification. The change in mollusk prices is modelled using a Cobb-Douglas production function with environmental quality as an input. Changes in household consumption of mollusks and alternative meats with respect to income and food prices is modelled using a two-stage demand system to estimate the parameters of a representative household's expenditure function. The estimated expenditure function is then used to calculate the additional income that a representative household would require to obtain their utility level under a "medium" ocean acidification scenario (Representative Concentration Pathways RCP8.5) versus a "high" ocean acidification scenario (RCP6). The present value of aggregated reduced consumer welfare is estimated to be US\$ 735 million for the period 2010-2100 using a discount rate of 5%. The author identifies the most tenuous link in the integrated model to be the relationship between changes in mollusk growth rates and prices. The Cobb-Douglas production function that is used is an assumed relationship (unitary price elasticity with respect to mollusk growth rates) rather than being empirically determined.

Cheung et al. (2011) simulate the impact of ocean acidification on the distributions and estimated catch potentials for commercially exploited demersal fish and invertebrates in the North-East Atlantic for the period 2005-2050. They construct a dynamic bioclimatic envelope model that accounts for the effects of changes in ocean biogeochemistry on the distribution, productivity and maximum catch potential of 120 fish and invertebrate species. Under the SRES A1B scenario, they show that the maximum catch potentials decline by 20–30% (10-year average for 2050 relative to 2005) relative to model simulations that do not account for ocean acidification and reduced oxygen availability. The paper discusses a number of sources of uncertainty in the analysis and shows that the distribution of physiological impacts of ocean acidification is highly dispersed.

Sumaila et al (2011) provide a review of the global impacts of climate change on capture fisheries, including the impacts of ocean acidification. The paper gives a qualitative discussion of the expected impacts of ocean acidification and argues that the likely effects are for potential catch to decrease, fish prices to increase, costs of fishing and adaptation to increase, and resource rents to increase. The reasoning for an increase in fishery resource rents is not explained. The paper concludes that there are substantial knowledge gaps in disciplinary and interdisciplinary understanding of the full range of

impacts and that current research is not necessarily focused on regions that are likely to experience the heaviest impacts.

Armstrong et al. (2012) describe a preliminary analysis of the potential impacts of ocean acidification in Norwegian waters. The study identifies the marine ecosystem services that are likely to be affected by ocean acidification, the economic methods to assess the impacts, and the present knowledge gaps. The study also produces a preliminary analysis of the scale of possible damage costs from ocean acidification with a focus on provisioning and regulating services. The results of this analysis show that ocean acidification may have positive as well as negative effects on provisioning services of fisheries and aquaculture. The largest estimated damage cost, however, is due to the reduced regulating service of carbon storage and the associated increased impacts of climate change.

Rodrigues et al. (2013) provide a discussion of the possible impacts of ocean acidification in the Mediterranean Sea. The sectors for which substantial impacts are considered likely are tourism and recreation, red coral extraction, capture fisheries and aquaculture production. In addition the study considers the effects of ocean acidification on carbon sequestration and non-use values. The framework and methods for conducting an economic assessment are set out and a preliminary qualitative assessment of potential impacts is made. This study is part of the “European Mediterranean Sea Acidification in a changing climate” (MedSeA) project funded by the European Commission and lays the basis for future quantitative assessments within this project.

Hilmi et al (2012)<sup>2</sup> summarizes the current understanding of potential impacts of ocean acidification and sets out what further information is required to enable social welfare analyses of ocean acidification. The paper does not review existing assessment results as we do in this chapter but aims to provide clear directions for future multidisciplinary collaborative research. The recommendations for data collection to inform socio-economic studies of ocean acidification include the collection of observational data on ocean chemistry, determination of the biological relevance of chemical changes, long-term multi-generation biological experiments, analysis of synergies between multiple stressors, assessment of ecosystem responses, and understanding the adaptation potential of marine ecosystems. The authors also argue for integrated quantitative assessments of the likely biological, social and economic impacts of ocean acidification, and emphasise the need for information on the vulnerabilities of both ecosystems and human communities.

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<sup>2</sup> This review paper was initiated following the first international workshop of the Monaco Environment and Economic Group (MEEG) on bridging the gap between ocean acidification impacts and economic valuation, jointly organized by the Centre Scientifique de Monaco and the International Atomic Energy Agency.

Harrowd-Kolieb et al. (2009) address the likely distribution of economic impacts and vulnerability to ocean acidification. Vulnerability is evaluated at the national level based on four equally weighted criteria, namely fish and shellfish catch, the level of seafood consumption, the extent of coral reefs as a percentage of exclusive economic zones (EEZ) and the projected level of ocean acidification in coastal waters in 2050. Countries are then ranked according to their acidification vulnerability score. The results of this ranking show that it is mainly developed countries that score highly in terms of vulnerability, with Japan, France, the United Kingdom, the Netherlands and Australia making up the top five. This analysis of vulnerability is arguably over simplified but points to the need for further analysis of this issue. In particular, there is a need for an analysis of vulnerability below the national scale since it is likely that the impacts of ocean acidification will be highly spatially variable with severe impacts in specific locations, e.g. coastal communities that are highly dependent on fisheries and coral reef ecosystem services, and that have low capacity to adapt.

Cooley et al (2012) also address the issue of vulnerability to the impacts of ocean acidification and focus their analysis on mollusk fisheries. They develop a national level vulnerability scale that first groups countries by net import status and then assigns a point for each of the following five characteristics: 1. Mollusk fisheries account for more than 0.001% of GDP; 2. The country is protein insufficient; 3. Mollusks account for more than 1% of dietary protein; 4. the increase in mollusk fishery production required to maintain constant per capita volume is greater than 100%; 5. The country does not currently have a mollusk aquaculture industry. Points are also assigned based on each country's adaptability ranking (based on characteristics 4 and 5 above) and on the estimated number of years until each country's EEZ is expected to experience substantial change in mean and variability of calcium carbonate availability. The expected "transition decade" in which a substantial change in calcium carbonate availability occurs is projected to vary across national EEZs within the range of 10-50 years from 2010. Countries with low adaptive capacity, high nutritional or economic dependence, rapidly growing populations, and rapidly approaching transition decades are therefore identified as the most vulnerable to ocean acidification impacts on mollusks. The highest ranked vulnerable countries are mainly least developed countries in sub-Saharan Africa. Again the scale of analysis at the national level may conceal severe impacts at a local or regional scale.

Huelsenbeck (2012) produces a similar analysis of vulnerability that includes the following factors: 1. Exposure (aragonite saturation state in EEZ by 2050); 2. Dependence (coral reef fishers as a proportion of the national population); 3. Dependence (mollusk consumption as a percentage of available protein); Adaptive capacity indicators (GDP per capita, population growth rate 2012-2050, percentage of the population under-nourished). In this analysis the countries at the top of the vulnerability ranking are again least developed countries but include some small island nations.

The studies reviewed here have assessed several of the expected impacts of ocean acidification on ecosystem services. Most have focussed on impacts to commercial fisheries and particularly mollusk fisheries. This is understandable given the relatively well understood relationship between ocean biogeochemistry and mollusk growth, albeit largely at the laboratory experimental level. The paucity of value estimates for the impact of ocean acidification on fin fisheries reflects the lack of current understanding of the biological/ecological processes involved.

The biophysical impact of OA on coral reefs is also relatively well understood (although recent research points to potentially complex feedbacks – Anthony et al., 2011; Kleypas et al., 2011) but the economic impacts have only been valued by one study to date. The economic valuation of coral reef ecosystem services is characterised by high complexity and uncertainty. This is largely due to the scarcity of information on the value of coral reef ecosystem services (particularly non-recreation services such as support to fisheries, coastal protection and non-use biodiversity values) and the non-market nature of many of these services. Since most coral reef services are not traded directly in markets, values are not readily observable. In response, there are a growing number of studies that apply non-market valuation techniques to estimate values for coral reef services but these are prone to biases and inaccuracies. Moreover there is a substantial methodological challenge in transferring existing value information that is inherently spatially variable to estimate values for impacted ecosystems in other (future) contexts (Brander et al., 2012).

The geographic scale of analysis of studies examining the economic impacts of ocean acidification has tended to be very large. Most studies cover a global scope with a level of analysis at either a regional or national scale. National assessments are only available for Norway and the US. Regional analyses have focussed on broad marine ecosystems (i.e. the Bering Sea) or FAO statistical regions (i.e., the North-East Atlantic, FAO Area 27). Cooley and Doney (2009) report results for specific sub-national regions, namely New Bedford, New England and the Pacific coast. The existing research has attempted to provide first estimates of the scale of the ocean acidification problem but it has not determined a spatial disaggregation of which human communities are most at risk. It is likely that ocean acidification will have highly localized ecological and societal impacts. The impact on economic welfare can be expected to vary across locations depending on the localised degree of acidification, the sensitivity of ecosystems to acidification and the extent to which they are already under pressure, the dependence of the population on impacted ecosystem services (e.g. fisheries, coastal tourism), and the capacity to adapt to losses in the provision of those services. All of these factors along the ocean acidification impact pathway vary by location and so it is important to have an understanding of their spatial convergence in order to identify where the impacts of ocean acidification will be most severe. Information on the spatial distribution of impacts is useful in order to target adaptation responses such as additional marine management, reduction in other environmental pressures and the development of alternative sources of protein and income.

Regarding the methodologies employed in the reviewed studies, a broad range of approaches have been used, particularly for the valuation of impacts. The welfare measures that have been estimated are therefore not consistent or directly comparable. Armstrong et al. (2012) estimate gross revenue from fisheries and damage costs from enhanced climate change; Cooly and Doney (2009) estimate loss of gross revenue; Narita et al. (2012) estimate changes in both consumer and producer surplus; Moore (2011) estimates the compensating variation measure of consumer welfare; and Brander et al. (2012) use a meta-analytic value function that is derived from a mix of underlying welfare estimates (including both consumer and producer surplus). A common methodological weakness in the reviewed studies is the link between biophysical changes resulting from ocean acidification and changes in the provision of ecosystem services. Cooly and Doney (2009), Narita et al. (2012) and Moore (2011) all use an assumed relationship between mollusk growth and harvest. Brander et al. (2012) use a very simple model of the impact of OA on coral cover and implicitly model the provision of ecosystem services through the meta-analytic value function.

Of the thirteen studies reviewed only five provide monetary estimates of the costs of ocean acidification. Three of these are for impacts on mollusk fisheries (two for the US and one global estimate); one covers impacts on fisheries and carbon storage; and one is for impacts on coral reef services. Central estimates from each study are presented in Table 1 and standardised to annual values in the terminal year of each analysis in US\$ at 2010 price levels. From the limited information that is currently available, it appears that impacts to coral reef services dominate. The global annual loss in value of coral reef services in 2100 is estimated to be an order of magnitude higher than that of mollusk fisheries. The estimated increased damage cost of climate change associated with reduced carbon storage due to ocean acidification suggests that this is also a potentially important impact category. The cost of this feedback effect to climate change has currently only been roughly estimated for the Norwegian Exclusive Economic Zone. The current information on the damage costs of ocean acidification only provides a partial assessment of total impacts given that other impact categories, particularly fin fisheries, are yet to be widely assessed. Gaps in the current knowledge are discussed in the following section.

Table 1. Summary of studies that examine the economic impacts of ocean acidification

Study	Impacts	Geographic scope	Emissions scenario	Period of analysis	Welfare measure <sup>1</sup>	Annual value (US\$; billions) <sup>2</sup>
Armstrong et al. (2012)	Fisheries	Norway	pH decrease 0.5	2010 – 2110	Revenue	0.01
	Carbon storage	Norway	pH decrease 0.5	2010 – 2110	Damage Cost	3
Brander et al. (2012)	Coral reefs	Global	SRES A1B	2000 - 2100	Mixed	1,093
Cheung et al. (2011)	Fish and invertebrates	N-E Atlantic	SRES A1B	2005 - 2050	-	-
Cooley and Doney (2009)	Mollusks	United States	IPCC A1F1	2007 - 2060	Revenue	0.07
Cooley et al. (2012)	Mollusks	Global	CCSM3	2010 - 2060	-	-
Finnoff (2010)	Fisheries; non-use values	Baring Sea	-	-	-	-
Harrould-Kolieb et al. (2009)	Coral reefs; fisheries	Global	SRES A1B	2009 - 2050	-	-
Hilmi et al. (2012)	All	Global	-	-	-	-
Kite-Powell (2009)	Coral reefs; fisheries	Global	IS92a	-	-	-
Moore (2011)	Mollusks	United States	RCP8.5; RCP6	2010 - 2100	CV	0.31
Narita et al. (2012)	Mollusks	Global	IS92a	2000 - 2100	CS, PS	139
Rodrigues et al. (2013)	Use and non-use values	Mediterranean	-	-	-	-
Sumaila et al. (2011)	Capture fisheries	Global	-	-	-	-

<sup>1</sup> CV: compensating variation; CS: consumer surplus; PS: producer surplus

<sup>2</sup> Impact estimates are standardised to annual values for the terminal year in each analysis (i.e., 2060 for Cooley and Doney (2009) and 2100 otherwise) in US\$ 2010 price levels.

#### **4. Gaps in current knowledge**

The literature overview demonstrates that there are still considerable gaps in knowledge. These gaps refer to (1) understanding the relation between changes in the marine environment and socio-economic impacts, (2) the ecosystem services that have been assessed, (3) the distribution of impacts and (4) the vulnerability of different populations. These individual gaps are discussed in more detail in this section.

The first gap relates to difficulties in linking impacts of ocean acidification on biophysical processes with changes in human benefits. Though natural science is starting to shed light on the functioning of marine ecosystems and the provision of ecosystem services, important links between ecosystem functioning, ecosystem services and human benefits are still poorly understood. However, it needs to be noted that even on the first level, the understanding of biophysical processes, important research gaps exist. The majority of studies look at direct impacts (growth, survival etc.) of ocean acidification on single species, mostly calcifying organisms (Fabry 2008). Studies focusing on other organisms and indirect effects, such as habitat changes, adaptation of marine species to changing conditions or food web effects, are very limited. Most existing studies are based on short-term perturbation experiments that do not account for regional differences in the coastal or marine environment. Another limitation is the type of information generated by natural science studies that can be used in economic impact analysis. Studies on the impact of ocean acidification on calcifying organisms generally analyse changes in calcification rates. However, in economic studies information on the potential change in harvest, for molluscs, or loss in reef area, for coral reefs, are required. Due to this lack of information, the studies reviewed in Section 3 that estimate the value of impacts are based on changes in calcification rates.

As biologists and ecologists still grapple with the first order impact of ocean acidification, little (quantitative) attention has been paid to more complex issues – such as variability, heterogeneity, non-linearity, threshold effects, and irreversibility– and higher order effects – such as predator-prey relations and resource scarcity.

The second gap identified regards the types of ecosystem services and values that have been analysed so far. The estimates that are currently available focus on particular aspects of direct use values (mollusk fisheries and coral reef recreation). Other ecosystem services with direct use values (e.g. fin fish) have not yet been considered. Likewise, other value categories including indirect use values (e.g. regulating services) and non-use values (e.g. existence and bequest values for marine biodiversity) have not been addressed. The existing estimates of the economic impact of ocean acidification are,

therefore, far from complete. It should be noted that in general goods and services provided by marine and coastal ecosystems have received far less attention in the economic valuation literature than those provided by terrestrial ecosystems. Since many marine ecosystem services are much less visible, valuation is a much greater challenge, which puts existing valuation approaches to the test.

Another important gap (3) in the current knowledge is on the distribution of impacts of ocean acidification. So far, research is practically absent as to the question of which groups of people will suffer economically from ocean acidification by how much. The importance of the distribution of impacts is twofold. First, better information about the distribution of impacts would enable governments to make plans and actions to support the coping efforts and adaptation by communities that are particularly affected by acidification. Second, information on how the impacts of ocean acidification are distributed influences our evaluation of the social welfare implications of ocean acidification, and in turn, of desirable stringency of general carbon policy to reduce the problem. For example, a deep reduction of carbon dioxide emissions might be warranted if the damage of ocean acidification disproportionately falls on the poorest regions of the world, since there are no effective public mechanisms that facilitate substantial international transfers of wealth.

For the understanding of impact distributions, both detailed local-level studies and synthetic global or regional studies need to be conducted and compared. Local-level studies are essential for the understanding of impact distributions for two reasons. First, as discussed earlier, the magnitude of biogeochemical impacts of ocean acidification are spatially heterogeneous because of local patterns of ocean circulations, differences in coupling effects with sea temperature or other local geological characteristics, and characteristics of local ecosystems. Only detailed local-level studies can take account of such local differences. Second, the importance of the marine environment to human welfare is spatially heterogeneous depending on local socio-economic conditions and cultural factors. For example, the significance of fisheries for people is different depending on the availability of species, income levels, dietary habits and other cultural traits, and the existence of alternative income sources. Often, a change in the marine environment brings about acute effects on the livelihoods of specific groups within a community, such as fishermen or those engaged in the tourism sector. Local-level studies can highlight such differences in impacts affecting different social groups.

Global or regional-scale studies are also important and are complementary to the local-level studies mentioned above. The values of marine ecosystem services are partly determined by their demand, which is determined by the availability of substitutes, the income level of consumers, and also how closely the economy is connected to the global market. To account for all these factors necessitates a general equilibrium analysis. In addition, the analysis of ocean acidification entails a long time horizon, and in this sense it is important to take account of expected economic growth and demographic changes in the future.

A related aspect to the distribution of impacts is vulnerability (4). Some populations will be relatively more vulnerable than others to the negative impacts of ocean acidification. In other words, the biophysical impacts of ocean acidification could incur varied monetary and non-monetary costs, especially in terms of long-term costs such as nutritional deficiency or low educational attainment as a result of losses in income and food availability. Vulnerability is determined both by a population's dependence on ecosystem services that are likely to be impacted by ocean acidification and by its adaptive capacity. Dependence is determined by the extent to which a community is reliant on fisheries and coral reef services for nutrition and income. Adaptive capacity is determined by the availability of substitute production and consumption options. For ocean acidification, there are a number of potential adaptation options. For example, aquaculture may be able to insulate itself from or mitigate the effects of acidification by relocating farms to closed waters or adopting varieties resistant to acidity (for a discussion, see Narita et al., 2012). Adaptation, however, generally incurs costs, and actions are warranted only if the benefits outweigh the costs. At present, little analysis has been done with regard to the costs of adaptation to ocean acidification, and more research is needed on this subject. In evaluating adaptation costs, it is important to consider the coupling of ocean acidification with other factors that affect the marine environment, such as more frequent storm surges or sea level rise under climate change.

## **5. Discussion and conclusions**

The assessment of the economic impacts of ocean acidification requires the understanding and quantification of each step in the impact pathway from carbon dioxide emissions through biogeochemical effects, impacts on species and ecosystem level processes, provision of ecosystem services, and finally to the value and distribution of economic impacts. Such assessments require the integration or linkage of multiple research disciplines. Environmental economics has all the tools available to analyse the economic impact of ocean acidification, but estimates are few because natural scientists have only recently been able to quantify the impact on organisms and ecosystems.

According to Table, 1, the annual impact of ocean acidification is measured in tenths of a per cent of global GDP. The impact of climate change on the other hand is measured in per cents (Tol, 2009). Ocean acidification is thus an additional reason for concern about carbon dioxide emissions, but given the large uncertainty about the total impacts, it is not a reason to drastically raise the level of concern.

Although the exact calculations are yet to be made, ocean acidification could have a much larger effect on the optimal Pigou tax on carbon dioxide emissions. The total impact of climate change is an order of magnitude larger than that of ocean acidification, but occurs some 50 years later than the

onset of significant acidification in the ocean. With a 5% discount rate and assuming a linear relationship between the degree of ocean acidification and its impact, the net present marginal value of ocean acidification and climate change are of the same order of magnitude (since  $1.05^{-50}=0.1$ ). Based on this approximate calculation, the estimated impacts reported in Table 1 suggest that the optimal tax on carbon dioxide emissions – but not on other greenhouse gases – should be doubled.

These quantitative insights are preliminary and incomplete. Many impacts remain unquantified and the currently available estimates have yet to be replicated. It is arguably even too early to structure or prioritise a research agenda. More work needs to be done on all economic aspects – impacts, adaptation, mitigation – of ocean acidification.

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