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Economic impact of ocean acidification on shellfish production in Europe

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Ocean acidification (OA) is increasingly recognized as a major global problem. Despite the scientific evidence, economic assessments of its effects are few. This analysis is an attempt to perform a national and sub-national assessment of the economic impact of OA on mollusc production in Europe. We focus on mollusc production because the scientific evidence on the biological impact on calcifying organisms is ample relative to other types of marine organisms. In addition, Europe and its regions are significant producers of marine molluscs. By performing a partial-equilibrium analysis, we show that the highest levels of overall impact are found in the countries with the largest current production, such as France, Italy and Spain. For Europe as a whole, the annual impact will be over 1 billion USD in 2100. Due to the different production foci of the individual countries and their regions, the distribution of the impact is extremely uneven across countries and their respective regions, with the most affected sub-national regions being those on the Atlantic coast of France, which is an important region for oyster production.

Keywords: climate change; economic assessment; Europe; ocean acidification; shellfish

1. Introduction

Described as ‘the other CO_2 problem’ (Doney *et al*. 2009), ocean acidification (OA) is gaining recognition in the policy debates on climate change and biodiversity (e.g., Secretariat of the Convention on Biological Diversity 2014). Governed by a well-known law of chemical equilibrium, enhanced atmospheric carbon dioxide due to human emissions shifts the balance of carbonate ions in seawater and lowers the pH of the ocean. Because atmospheric carbon dioxide is evenly mixed around the world, OA is a global problem, though some regional heterogeneity of effects exists because of the differences in ocean circulation, ocean temperatures and evaporation rates. Early calculations indicate that the global average pH of surface seawater (approximately 8.1) would be reduced by 0.3−0.4 by the end of the twenty-first century under the business-as-usual emission scenario (Caldeira and Wickett 2003, 2005). The latest IPCC Assessment Report (2014) concludes that under its medium to high-emission scenarios, OA could pose detrimental consequences for fisheries and the livelihoods of fishery operators.

Along with scientific research on OA, attempts to perform an economic analysis of OA in monetary units − focusing on the damage to shell fisheries and ecosystem services provided by coral reefs, including recreation/tourism opportunities, coastal protection

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*Corresponding author. Email: katrin.rehdanz@ifw-kiel.de and reef related fisheries – have been made (Brander *et al*. 2014 review the literature of economic analysis of OA). An economic assessment of OA is useful for the following reasons. First, an estimation of the potential economic damage of OA could help policymakers plan investments for developing adaptation options in anticipation of future effects. Second, as OA occurs along with climate change as a result of human carbon dioxide emissions, an economic assessment of its impact is needed for an accurate estimation of the social cost of carbon[1] to provide a basis for global debates on climate change mitigation. Significant economic costs from OA would imply that the optimal mix of greenhouse gas reduction could not be evaluated only by their relative atmospheric warming potential. It is also worth noting that estimating the relative impact of OA could have particular implications for devising climate change mitigation strategies as some measures of climate (or geo-) engineering, such as solar radiation management, are not effective for controlling OA (Williamson and Turley 2012).

Scientific information about the biological and ecological impact of OA on marine organisms is still very limited, and thus quantitative economic studies of OA have so far been focused on types of marine organisms on which the effects of acidification are relatively well known – namely, corals and molluscs (see Brander *et al*. 2014 for a review). Brander *et al*. (2012) attempt to make a global economic assessment of the ecosystem services of coral reefs under OA conditions using an integrated assessment model of climate change (FUND model), where ecosystem services of coral reefs are considered largely recreational services. Cooley and Doney (2009) estimate the losses of US mollusc fisheries affected by OA by assuming damage for the industry proportional to the calcification loss rates of molluscs reported in the literature of biological experiments in acidified environments. Narita, Rehdanz, and Tol (2012) conduct a global analysis that also estimates the damage as proportional to the calcification loss rates drawn from a meta-study, but this analysis is based on a partial-equilibrium approach that could take into account the effects of price shifts. Though supported with only limited empirical information, Moore (2015) attempts to perform a complete welfare analysis of mollusc production and consumption in OA conditions that considers the expenditure function of representative households in the US. A group of studies related to these economic assessments is the study of the vulnerabilities of fisheries to OA (Cooley *et al.* 2012; Ekstrom *et al*. 2015). As they refrain from the use of economic projections, these studies have the advantage of basing their analyses only on solid scientific data. While their results are useful for identifying the near-term adaptation strategies of fisheries for OA, their analyses do not show the values of OA losses explicitly and thus are not directly relatable to the debates on climate change mitigation policies. It is also worth noting that some reference to economic projections is inevitable to reflect on the long-term strategies of both mitigation and adaptation as the production of shellfish is determined not only by marine environment conditions but also its demand.

This paper contributes to the existing literature by focusing on the economic impact of OA on shellfish production in Europe and its sub-national regions. In Europe, compared to other regions, the status of policy discussions on OA is relatively advanced (see e.g., Hilmi *et al*. 2014). Our results, therefore, are relevant to direct policies. Furthermore, and as indicated above, earlier studies have examined the global economic impact (e.g., Narita, Rehdanz and Tol 2012) or a specific country (e.g., Moore 2015). So far, no study has investigated sub-national regions with a comparison of individual countries. Europe is particularly interesting for this type of regional study because of the diversity of harvested species in Europe (e.g., oysters in France and mussels on the continental North Sea coast) and the range of environmental conditions of marine waters across the region (see Hilmi *et al*. 2014 for an overview). In addition, Europe is the second-largest global aquaculture producer of molluscs and the fourth-largest marine molluscs capture producer.[2] In our analysis, we rely on the partial-equilibrium approach and estimate the country-specific and sub-national economic costs of the production loss of molluscs (impact on both producer and consumer surpluses) due to OA in 2100 in a business-as-usual emission scenario.

The paper is structured as follows. Section 2 briefly summarizes the scientific facts of OA that serve as the basis for our analysis and provides information on the state of the European economy regarding the consumption and production of shellfish in Europe. Section 3 presents our approach of the partial-equilibrium analysis and the data used. Section 4 shows the results, and Section 5 concludes.

2. Biological impact and the state of the economy

2.1. Biological impact

OA could harm the growth and survival of marine organisms through both direct (i.e., the disturbance of physiological processes) and indirect (i.e., changes in ecological interactions) effects (IPCC 2011). Biological research on this subject is only emerging, but a relatively large amount of information exists for the direct effects of acidified water on calcifying organisms, such as molluscs and corals. Recent meta-studies find that direct negative effects are at least significant for molluscs (Hendriks, Duarte, and Alvarez 2010; Kroeker *et al.* 2010, 2013). A caveat for this finding is that these studies are based on only short-term experiments and that the magnitude (and possibly the sign) of these effects can be different across different species of molluscs (Wittmann and Pörtner 2013). Meanwhile, the indirect effects of OA and its combination with other stressors for marine organisms (ocean warming, habitat destruction, overexploitation, eutrophication and other forms of chemical pollution, spread of invasive species) could exert potentially serious, though still largely unknown, negative effects (IPCC 2011).

Although research-based evidence is even scarcer, there are some indications that many biological functions other than calcification could also be affected by OA and, consequently, that the direct effects of acidification may appear in a wide range of organisms from fish to bacteria (IPCC 2011; Hilmi *et al.* 2013). At the same time, however, it is also known that some marine organisms, such as phytoplanktons and some seagrass species, may benefit from low pH levels and could thus potentially thrive under OA (IPCC 2011; Hilmi *et al.* 2013).

2.2. State of the economy

Before turning to the quantitative assessment of the impact of OA in Europe, we explore the state of European economies regarding shellfish consumption, production and employment in fisheries. We do so specifically to investigate whether regional differences that are significant in terms of impact assessment are likely to exist. For the Mediterranean countries, Hilmi *et al.* (2014) summarize fishery statistics with a similar scope to ours.

Table 1 shows the average annual consumption of total seafood and molluscs in European countries for the 2001–2010 period. The consumption patterns of molluscs indicate a high level of heterogeneity across European countries. Most countries have low per capita consumption of less than 1 kg per year, but a few countries – such as Belgium, Denmark, Iceland, Italy and Portugal (with over 3 kg per capita per year) as

Table 1. Average annual consumption of total seafood and molluscs in European countries (kg per year per capita; averaged over 2001–2010).

Country	Total seafood[1]	Molluscs[2]	% of molluscs to the total
Albania	4.7	0.3	6
Belgium	24.3	4.3	18
Bosnia and Herzegovina	5.8	0.2	3
Bulgaria	4.9	0.1	3
Channel Islands	na	na	na
Croatia	16.1	1.5	10
Denmark	22.6	3.5	15
Faroe Islands	na	na	na
France	34.0	7.6	22
Germany	14.5	0.5	4
Greece	21.0	1.0	5
Iceland	90.4	3.1	3
Ireland	22.1	2.3	10
Isle of Man	na	na	na
Italy	24.8	4.2	17
Lithuania	41.4	0.2	1
Montenegro[3]	9.7	0.7	7
Netherlands	21.2	0.7	3
Norway	51.6	0.7	1
Portugal	55.8	3.6	6
Romania	4.9	0.0	1
Serbia and Montenegro[4]	3.7	0.1	2
Slovenia	9.5	0.7	7
Spain	42.7	6.2	14
Sweden	31.5	0.7	2
Ukraine	15.2	0.3	2
United Kingdom	20.3	1.2	6
European average	24.7	1.8	7

[1] Data of ‘fish, seafood + (total)’ from the FAO Food Balance Sheets.
[2] Data of ‘Molluscs, Other’ from the FAO Food Balance Sheets.
[3] Average for the period 2006–2010.
[4] Average for the period 2001–2005.

well as Spain and France (with over 6 kg per capita per year) – exhibit significantly larger amounts of per capita consumption. The table also shows that some countries with high seafood consumption levels in general do not consume large amounts of molluscs (such as Iceland, Norway and Lithuania).

Regarding the production of molluscs in European countries, Table 2 indicates that for the average annual production, a high level of heterogeneity across European countries also exists for the 2001–2010 period. The majority of European countries produced less than 10,000 tons of molluscs per year during that period. However, the Netherlands, Spain and France are exceptions with production of above 100,000 tons; France is closer to 200,000 tons. Regarding the group of species produced, mussel production clearly dominates. For most countries, more than half of their mollusc production is allocated to mussels. Among the countries with significant mollusc production, France is the only country with a large share of oyster production. The percentage of clams, cockles and ark shells overall is rather negligible.

Looking at the type of production used, significant differences also exist across Europe (Table 2). However, most countries with significant mollusc production (>10,000 tons) predominantly use aquaculture techniques (France, Germany, Greece, Ireland, the Netherlands and Spain) while countries such as Denmark and the UK rely on capture fisheries for mollusc production.

Overall, these initial insights highlight that the impact of OA on consumers and producers will be very differently distributed across Europe. For example, it seems to not

Table 2. Average annual production of marine molluscs in European countries (2001−2010).

Country	Total marine molluscs production (tonnes)	Marine mussel production (% of total production)	Marine oyster production (% of total production)	Marine clam, cockle and arkshell production (% of total production)	Marine aquaculture molluscs production (%)
Albania	255	99	0	0	99
Belgium	677	na	na	na	0
Bosnia and Herzegovina	17	58	42	0	100
Bulgaria	380	5	0	0	2
Channel Islands	470	0	52	0	52
Croatia	575	92	3	0	94
Denmark	62,265	99	0	0	0
Faroe Islands	1,868	na	na	na	0
France	185,899	22	61	0	83
Germany	22,313	93	0	1	93
Greece	11,367	85	5	0	58
Iceland	4,677	0	0	1	0
Ireland	14,381	71	6	0	68
Isle of Man	3,142	0	0	0	0
Italy	87,074	57	1	4	49
Lithuania	<1	na	na	na	0
Montenegro	1	na	na	na	0
Netherlands	104,387	84	1	1	85
Norway	4,447	13	0	0	12
Portugal	6,428	1	13	8	52
Romania	<1	100	0	0	0
Serbia and Montenegro	<1	100	0	0	100
Slovenia	63	99	0	0	99
Spain	161,846	87	1	1	89
Sweden	785	98	2	0	97
Ukraine	143	69	0	0	20
United Kingdom	43,812	24	2	4	10
European total	717,726	61	9	1	58

Source: Own calculation based on FAO Fishstat data.

necessarily be the case that molluscs are consumed where they are produced. Households in the Netherlands consume relatively low amounts of molluscs despite its significant production. Table 3 confirms this by providing information on average annual trade quantities and values for the 2001–2010 period. A positive (negative) sign indicates an export (import) surplus. For countries such as Spain, Denmark, Ireland and the Netherlands, the value of net exports of mussels exceeds 10 million USD per year; the Netherlands produces close to 100 million USD per year. France is a significant net exporter of oysters, clams, cockles and ark shells (annual value of over 10 million USD)

Table 3. Average annual trade volume and value of marine molluscs in European countries (2001–2010)[1].

	Trade quantity (tonnes) (export−import)			Trade value (000 USD) (export−import)		
Country	Mussels	Oyster	Clam, cockle and ark shell	Mussels	Oyster	Clam, cockle and ark shell
Albania	−2	−1	0	−5	−3	0
Belgium	−26,653	−2,101	−123	−92,931	−10,381	−479
Bosnia and Herzegovina	−9	0	0	−39	−1	0
Bulgaria	−47	−4	−2	−167	−22	−11
Channel Islands	0	0	0	0	0	0
Croatia	−183	−1	−1	−593	−7	−2
Denmark	24,960	651	−1	40,271	4,751	9
Faroe Islands	−105	7	0	−201	63	0
France	−51,576	3,908	1,252	−88,178	24,637	11,374
Germany	−15,362	−670	−23	−10,587	−3,117	−69
Greece	13,447	−23	236	7,634	−109	1,208
Iceland	−8	0	87	−61	0	406
Ireland	16,906	2,380	1	35,927	8,634	7
Isle of Man	0	0	0	0	0	0
Italy	−28,769	−5,920	666	−43,290	−18,767	4,978
Lithuania	−42	−22	0	−123	−56	0
Montenegro	−4	0	0	−26	−1	0
Netherlands	21,551	1,790	−65	98,457	5,954	−151
Norway	1,294	−32	0	682	−262	0
Portugal	−2,057	108	−3,940	−6,055	150	−8,030
Romania	−99	−10	−5	−401	−65	−43
Serbia and Montenegro	−12	−2	0	−45	−1	0
Slovenia	−140	−6	0	−437	−34	−3
Spain	24,893	−2,928	−11,759	12,645	−12,533	−43,096
Sweden	−605	−163	−1	−2,671	−510	−1
Ukraine	−222	−43	0	−471	−550	0
United Kingdom	8,939	487	−7	−3,676	1,791	−22
European total	−13,904	−2,596	−13,683	−54,341	−436	−33,926

[1] Data of 'mussels, oysters, clams, cockles and arkshells prepared/preserved, live/fresh/chilled, other than live/fresh/chilled' from FAO Fishstat data. Own calculation.

but is also a significant net importer of mussels (annual value of over 88 million USD). Interestingly, Italy and Germany produce large amounts of marine mussels (Table 2) but are also large net importers (annual value of over 10 million USD and 43 million USD, respectively).

Employment in the fishery sector shows a high level of heterogeneity across European countries (the data are shown in Table 1.1 in the Appendix). Employment is low in some countries, e.g., Belgium, where only a few hundred fishery workers are employed. Other countries have higher employment levels in the fishery sector, with Greece, Italy and Spain possessing the largest numbers of fishery workers (over 20,000). In all European countries, however, the total size of employment in the fishery sector is approximately 10,000 persons at most and has been declining for decades; hence, any loss of employment in the sector as a result of OA would have only a negligible macroeconomic impact.[3]

The top three nations in terms of employment are France, Spain and Italy. Greece is a prominent country with regard to fisheries in general but does not have a large mollusc aquaculture production sector. More workers are employed in mollusc aquaculture than total capture fisheries (molluscs and also others) in France, but this is not the case in Spain and Italy. The European Commission Joint Research Centre (2013) reports that the mollusc aquaculture sector in France mainly produces Pacific cupped oysters (*Crassostrea gigas*), blue mussels (*Mytilus edulis*) and Mediterranean mussels (*Mytilus galloprovincialis*), whereas the main cultivates species are Mediterranean mussels in Spain and Venus clams and Mediterranean mussels in Italy.

3. Quantitative assessment

As noted in the previous section, the actual impact of OA on molluscs is likely to appear as a result of complex interactions with various other stressors and ecosystem functions, but in this analysis, we attempt a simple and transparent estimation that can be used as a benchmark to inform policy-making. To this end, we use as the basis of acidification loss data from biological experiments. This is solid data relative to other types of information (e.g., information from the actual events of increased water acidity in the natural environment, which is low). Kroeker *et al.* (2013) report estimates of four measures regarding the damage of OA on molluscs: survival, calcification, growth and development. Out of those four estimates, we adopt the value of calcification loss (40%) – the largest in effect size among the four – and the value of growth loss (17%) – the smallest – for our analysis. On the one hand, the actual loss of production could be smaller than those figures of calcification and growth loss if molluscs with lower levels of calcification and growth in OA conditions are still marketable as seafood. On the other hand, it is also possible that our use of the calcification and growth loss rates as a proxy for production loss could result in an underestimation of the impact if both types of damage occur independently to individual molluscs.

Kroeker *et al.*'s meta-study-level data are not sufficient for identifying the distinct effects on different species of molluscs, and consequently, we do not consider the heterogeneous impact of OA by species. This is likely to be an oversimplification, but scientific information is still lacking regarding the different levels of impact present across different species of commercial importance (Hilmi *et al.* 2014). Additionally, our analysis has limitations in that it does not reflect the combined effects of OA and temperature change because the information of the combined effects on molluscs is lacking at a meta-study level.

A large fraction of mollusc fisheries today employs aquaculture. In some of the cases that we consider, we distinguish mollusc production from capture fisheries and aquaculture, which may have different responses to OA. Aquaculture, which utilizes a controlled water environment, could, in principle, insulate itself from the effects of OA by manipulating the acidity of the cultivating water. However, as molluscs feed on plankton, which is commonly found in open marine environments, mollusc aquaculture practices normally involve some period of cultivation in open water. Hence, staving off the higher acidity of seawater is likely to add extra costs to aquaculture, if not making it impossible to finance. Billé *et al.* (2013) discuss the possibilities of adaptation for fishery management in OA conditions. In any event, there is a strong reason to assume that both capture fisheries and mollusc aquaculture production are affected by acidification. In this analysis, we simply assume that acidification equally affects capture fisheries and aquaculture.

Regarding the production quantities of molluscs, we base our estimates on data provided by the FAO Fisheries and Aquaculture Department.[4] Annual information on total aquaculture and capture production by country is obtained for the 2001−2010 period. The FAO database contains the data of aquaculture production in monetary value (USD) by country and species. Our aquaculture data-set covers 54 gastropod and bivalve species belonging to the following six species groups: ‘abalones, winkles and conches’, ‘oysters’, ‘mussels’, ‘scallops and pectinids’, ‘clams, cockles, and arkshells’, and ‘marine molluscs nei, other’.[5] Meanwhile, the FAO database does not include the data for capture production in monetary value (it only has volume data). In other words, the value data provided by the FAO are not directly usable for our analysis because they neglect the value of molluscs from capture fisheries. To compensate for this insufficiency of FAO data on capture fisheries, we assume that the prices for capture and aquaculture are the same for the identical species and estimate the values of captured molluscs by using the imputed prices from the value and quantity data of mollusc aquaculture from the FAO database. Additionally, to supplement the analysis on the country level with an analysis on the sub-national level, we use the Sea Around Us database that provides sub-national information on aquaculture production quantities for mollusc species.[6,7] By using these data, we assume that the regional share of mollusc capture production in a country is equivalent to the regional share of aquaculture production for a species group. Further information on the sub-national analysis is provided below. Note that our dataset of mollusc fisheries does not include values of recreational fisheries, for which few data exist but whose levels are presumed to be high (Hilmi *et al.* 2014).

We estimate losses of OA by using two methodological approaches. One approach is a simple multiplication (coded as ‘simple’ in our cases) of the total value of mollusc production and a loss rate (i.e., without price effects), which has the benefit of simplicity and clarity but does not reflect potential changes in demand of molluscs through the price adjustment from shifts in supply in OA conditions. The other is a partial-equilibrium model (‘parteq’) previously used by Narita, Rehdanz and Tol (2012). A partial-equilibrium approach captures the effect of a potential price shift due to the tightening of supply from OA and can show how the losses would be distributed between producers and consumers. The mollusc market is represented with demand and supply curves, and OA is assumed to shift the supply curve (uniformly) to the left. The slopes of the demand and (current) supply functions are set to be consistent with the representative values of the demand and supply elasticities of molluscs. We use the same values of elasticities as in Narita, Rehdanz and Tol (2012), which draw on parameter values of the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model by the International Food Policy Research Institute.[8] A graphical representation of our partial-equilibrium model is shown in the Appendix (Figure 1.2).

We also examine two sets of cases in which the demand for molluscs is kept at the current level and is increased according to future income growth. Based on IPCC's Representative Concentration Pathway (RCP) 8.5 scenario, the levels of OA considered in Kroeker *et al.*'s (2013) meta-study broadly correspond to the levels for the year 2100. Hence, we estimate and present figures as the losses of mollusc production due to OA in the year 2100 relative to the case without OA.[9] This choice of time point is not ideal to relate the results to the discussions of the near-term adaptation of mollusc fisheries because the year 2100 is too far in the future, but it is convenient for the discussions on climate change mitigation policies.

As for IPCC's RCP 8.5, the scenario itself does not specify GDP figures, but as the RCP 8.5 scenario is an extension of IPCC's A2 scenario (Riahi *et al*. 2011), we use the country breakdown figures of the global GDP values of the A2 scenario estimated by van Vuuren, Lucas, and Hilderink (2007) and Gaffin *et al*. (2004) (coded as "V" and "G" in our cases). Setting the year 2005 (the mid-year of the averaging period) as the base year, we calculate the income growth of individual countries from that year to the year 2100 and then increase in the demand for molluscs by using the income elasticity figures used in Narita, Rehdanz, and Tol (2012), which originally come from the IMPACT model.[10]

4. Results

Figure 1 displays the estimated annual economic loss (i.e., the decrease from the baseline without OA) in Europe in 2100 due to damage to mollusc production in OA conditions.

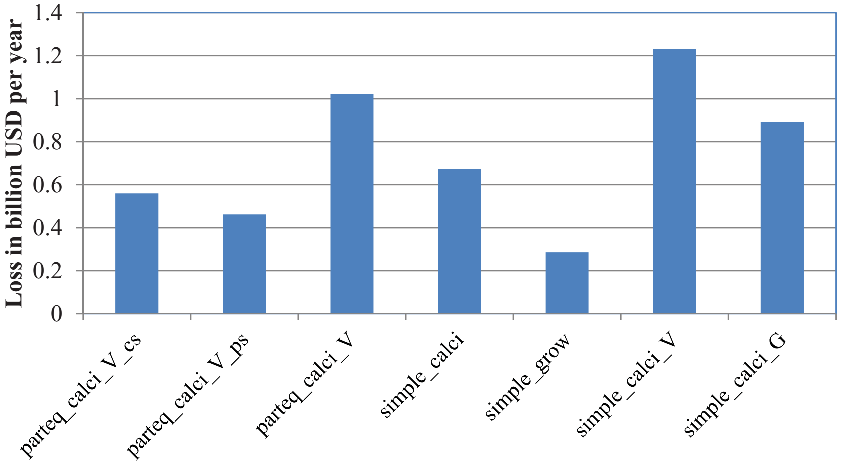

Figure 1. Estimated annual economic loss in Europe in the year 2100 due to damage on mollusc production under ocean acidification.

Note: parteq_calci_V_cs: Acidification consumer surplus loss based on calcification loss and van Vuuren 2100 income, total mollusc fisheries.

parteq_calci_V_ps: Acidification producer surplus loss based on calcification loss and van Vuuren 2100 income, total mollusc fisheries.

parteq_calci_V: Net total loss based on calcification loss and van Vuuren 2100 income, total mollusc fisheries.

simple_calci: Without price and income effects based on calcification loss, total mollusc fisheries.

simple_grow: Without price and income effects based on growth loss, total mollusc fisheries.

simple_calci_V: Without price effects based on calcification loss and van Vuuren 2100 income, total mollusc fisheries.

simple_calci_G: Without price effects based on calcification loss and Gaffin 2100 income, total mollusc fisheries.

As mentioned in the previous section, we estimate the values using the basis of the estimated calcification loss and growth loss rates (coded as 'calci' and 'growth', respectively). A simple estimate of loss without taking into account the effects of future income growth and price adjustments yields 0.67 billion USD annually, 55% of which (0.37 billion USD) comes from the loss of aquaculture (results not shown). With the income and price effects included, the total loss in Europe amounts to nearly 1 billion USD annually (parteq_calci_V). The estimated loss is much lower when the growth loss rate is used instead of the calcification loss rate (simple_growth). This is true for all cases of estimation. When considering future income growth, the impact significantly increases for all cases of estimation. In general, the levels of loss vary significantly depending on the basis of income projection, despite the fact that the two data-sets used here are country-level decompositions of the same IPCC scenario: the effect is much more pronounced when using the van Vuuren, Lucas, and Hilderink (2007) data compared to the Gaffin *et al.* (2004) data (as an example, compare simple_calci_V and simple_calci_G). When comparing the simple multiplication and the comprehensive partial-equilibrium approach, the loss is smaller for the more inclusive partial-equilibrium approach (as an example, compare simple_calci_V and parteq_calci_V), which reflects the price mechanism that adjusts the demand of molluscs. These are general findings. Additionally, the loss of consumer surplus is, generally speaking,

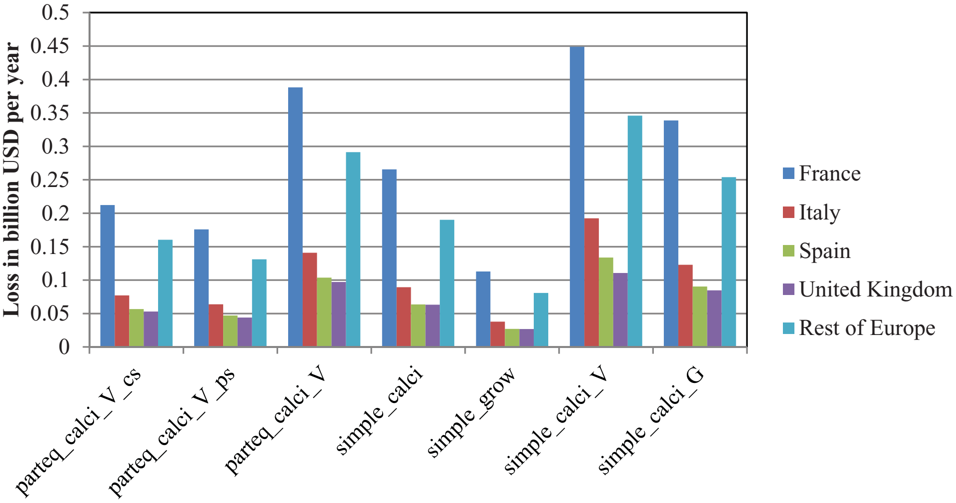

Figure 2. Estimated annual economic loss in selected European countries in the year 2100 due to damage on mollusc production under ocean acidification. See online colour version for ease of interpretation.

Note: parteq_calci_V_cs: Acidification consumer surplus loss based on calcification loss and van Vuuren 2100 income, total mollusc fisheries.

parteq_calci_V_ps: Acidification producer surplus loss based on calcification loss and van Vuuren 2100 income, total mollusc fisheries.

parteq_calci_V: Net total loss based on calcification loss and van Vuuren 2100 income, total mollusc fisheries.

simple_calci: Without price and income effects based on calcification loss, total mollusc fisheries.

simple_grow: Without price and income effects based on growth loss, total mollusc fisheries.

simple_calci_V: Without price effects based on calcification loss and van Vuuren 2100 income, total mollusc fisheries.

simple_calci_G: Without price effects based on calcification loss and Gaffin 2100 income, total mollusc fisheries.

slightly greater than the loss of producer surplus; in other words, the consumers suffer slightly more than the producers from acidification.

At the national level, large differences exist. Figure 2 shows the estimated annual economic loss in 2100 in selected European countries due to damage to mollusc production in OA conditions. Irrespective of the scenario, France incurs by far the largest loss, followed by Italy, the UK and Spain. The loss for France is 0.27 billion USD in the estimation without price and income effects (simple_calci) and 0.39 billion USD in the estimation with the two effects (parteq_calci_V).

As for the specific impact for aquaculture and capture mollusc production, the production of mussels is dominated by aquaculture and the production of oysters is nearly exclusively produced through aquaculture. The loss of mussel production is 0.22 billion USD in the estimation without the price and income effects and 0.33 billion USD in the estimation with the effects. Aquaculture is dominant in France and Spain, whereas capture is dominant in the UK.

Figure 3 extends the analysis by providing information on the estimated annual economic loss by country and species group (parteq_calci_V scenario). The size of the circles displays the extent of the loss while the division indicates the distribution of economic loss across the three species groups. Following Figure 3, the overall impact is greatest in France, Italy and Spain (over 0.1 billion USD), but the impact is also significant in the UK, Denmark and the Netherlands (between 0.06 and 0.1 billion USD).

The distribution of the impact across species groups is not even. Among the three groups of species, net losses in France are highest for oysters (0.23 billion USD), while in the Netherlands, Denmark, Ireland and Spain, the impact is greatest for mussels (0.07, 0.07, 0.01 and 0.05 billion USD, respectively); in Italy, Portugal and the UK, the

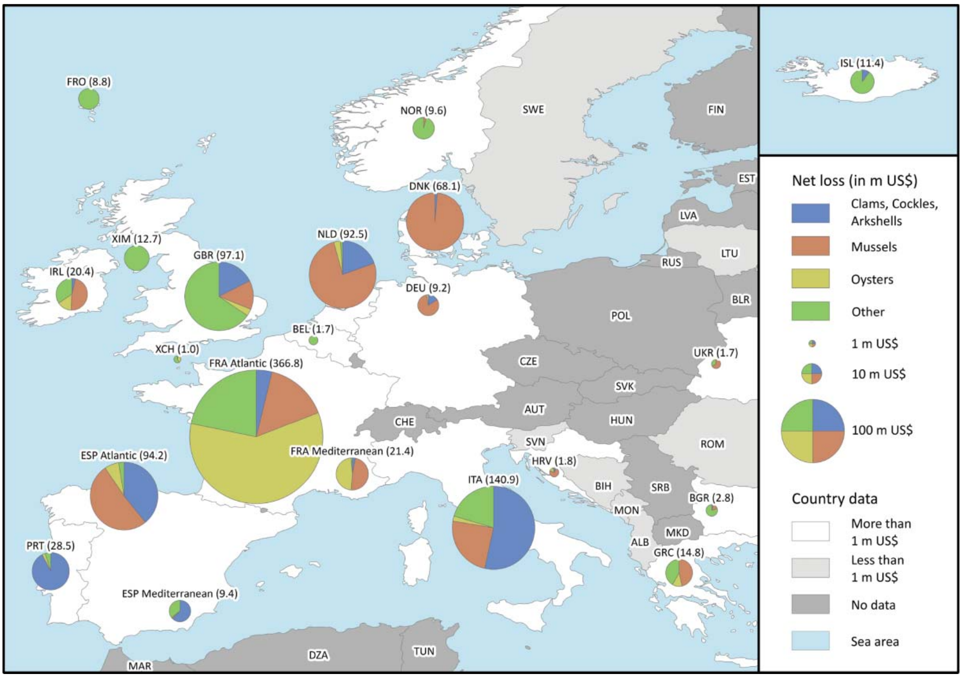

Figure 3. Estimated annual economic loss in Europe in the year 2100 due to damage on mollusc production under ocean acidification for selected species groups (parteq_calci_V scenario). See online colour version for full interpretation.

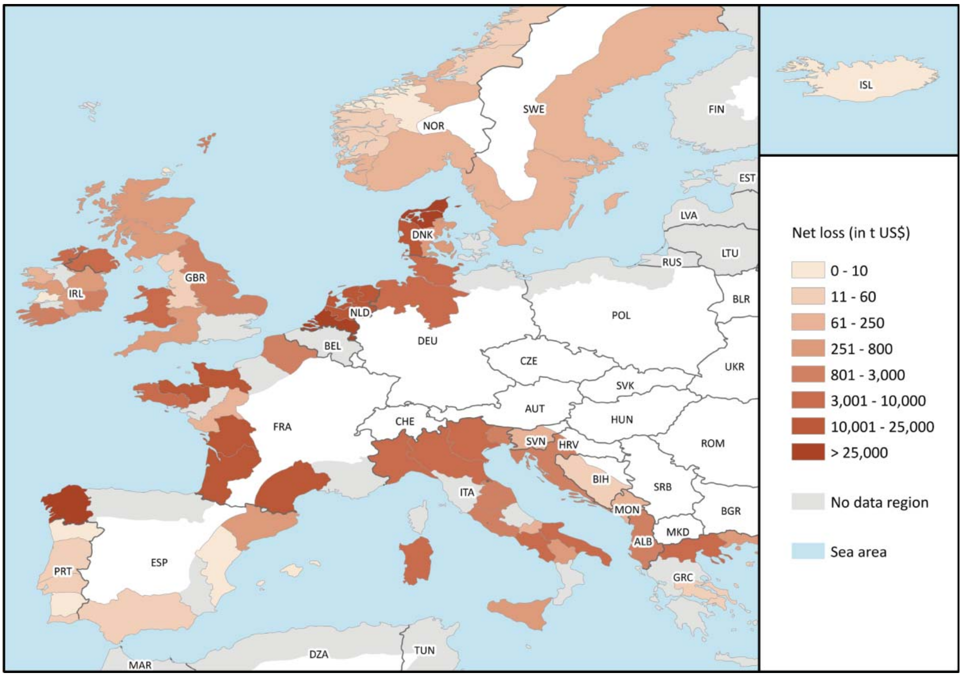

Figure 4. Estimated annual economic loss in sub-national regions of Europe in the year 2100 due to damage on mussel production under ocean acidification (parteq_calci_V scenario). See online colour version for full interpretation.

impact on clams, cockles and ark shells is highest (0.07, 0.03 and 0.02 billion USD, respectively).

Overall, the results thus far have demonstrated that a high level of heterogeneity across European countries exists regarding the economic impact of OA on mollusc production. Furthermore, and especially due to the different production foci within these countries, the distribution of the impact is very uneven across the countries. However, heterogeneity exists across and within countries. To take these facts into account, we use our results for an analysis on the sub-national level.

Figure 4 displays the estimated annual economic loss by region for oysters (parteq_calci_V scenario). From the data above, we know that losses are unevenly distributed across countries. Figure 4 suggests the same for the sub-national level. Some regions will suffer more than others. France is the country with by far the largest production of oysters and, according to Figures 2 and 3 above, the country with the largest impact on oyster production. Its production mostly uses aquaculture, and this means that finding adaptation methods of aquaculture practices to OA would greatly reduce the level of the total potential loss. At the sub-national level, a similar pattern emerges. Regions in France (for which we have data) will be affected more heavily than almost any other region in Europe. Three regions in France seem particularly vulnerable: Poitou-Charentes, Basse-Normandie and Southern Bretagne (approximately 89, 44 and 30 million USD). The only other sub-national regions within Europe (for which we have data) that show a significant impact include Galicia in Spain, Zeeland in the Netherlands and Attica in Greece.

Figure 5 displays the estimated annual economic loss by region for mussels (parteq_calci_V scenario). Again, we find large differences between regions. Unlike oyster production, which is concentrated in France, there are many more countries in

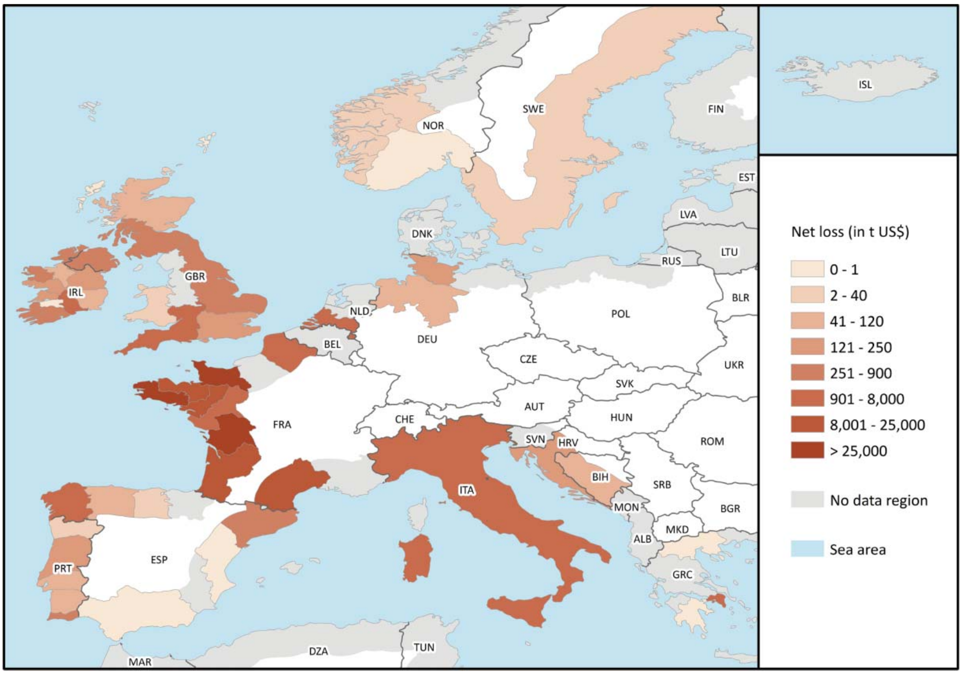

Figure 5. Estimated annual economic loss in sub-national regions of Europe in the year 2100 due to damage on oyster production under ocean acidification (parteq_calci_V scenario). See online colour version for full interpretation.

Europe that contribute significantly to the mussel production of Europe: the Netherlands, Denmark, France, Italy and Spain (Figure 3). For the Netherlands, all regions are heavily affected, but those in the south are slightly more affected (approximately 34 million USD in Zeeland). For Denmark, the impact is larger for regions on the West Coast. For Spain, the impact is largest in regions near the North Atlantic (Galicia) and is much less pronounced in regions near the Mediterranean Sea. For France, this difference is less clear. The differences between regions in Italy do not seem very pronounced.

5. Discussion and conclusion

This analysis is an attempt to generate a national and sub-national assessment of the economic impact of OA on mollusc production in Europe. We focus on mollusc production because the scientific evidence on the biological impact on calcifying organisms is ample relative to other types of marine organisms. In addition, Europe and its regions are significant producers of marine molluscs.

Our results show that the highest levels of overall impact are found in the countries with the largest current production, such as France, Italy and Spain. For Europe as a whole, the impact is over 1 billion USD annually in 2100. Due to the different production foci of the individual countries and their regions, the distribution of the impact is very uneven across countries and country regions. According to our scenario analysis, the sub-national regions that would be most affected are the regions on the Atlantic coast of France, which currently contribute significantly to oyster production.

The figures we obtained are broadly consistent with the estimates by other studies despite differences in methodology. Moore (2015) estimates that the annual consumer welfare impact of mollusc loss due to OA in the US at approximately 440 million USD by the end of the century by using the basis of 431 million USD of US expenditure on molluscs in 2010. Our analysis also shows similarity in the order between the 2100 loss in consumer surplus (0.6 billion USD for parteq_calci_V) and the baseline level of mollusc production (1.7 billion USD) in Europe. Meanwhile, Armstrong *et al.*'s (2012) scoping study on Norway shows that OA may cause approximately 74 million Norwegian Krone (approximately 9.6 million USD) of loss in provisioning services (including the provisioning of seafood) in 2110 (the worst case with a 0% discount rate) without including the income effect. In our analysis, a loss of 7 million USD for Norway in 2100 is estimated for a case without income and price effects considered (simple_calci).

As expected, our estimates are small compared to the estimates of the total economic costs of climate change: most integrated assessment models predict greater than 1% total GDP loss globally assuming a significant increase (i.e., >2 °C) of the global average surface temperature (Tol 2009, 2014), whereas the global total GDP is 76 trillion USD at present (the 2013 value in current USD according to World Development Indicators). However, it needs to be noted that we look only at a relatively small portion of fisheries for mollusc production. The total impact of OA on fisheries may be much greater than our estimate. Moreover, the ocean provides values greater than those associated with fisheries, including recreational values and symbolic values of marine environments and organisms, and this non-fishery ocean activities will also be affected by OA.

The estimation of economic losses of OA in concrete numbers, such as the one in this study, has the advantage of being usable for various types of discussions, including those regarding climate change mitigation policies. However, the scarcity of scientific data on OA poses limitations to our analysis in various ways, such as our singular focus on a year in the distant future (the year 2100). A deeper accumulation of scientific evidence would improve the accuracy of a similar analysis and the usefulness of the obtained estimates. Data for the differentiated impact by species and pH level at a meta-study level would be beneficial for economic assessment, as well as the data on the combined effects of pH and other stressors (e.g., pH + temperature). Indeed, European waters exhibit substantial regional differences in changes in pH and ocean temperature. Additionally, an economic assessment would benefit from biological impact information evaluated in the actual ecosystems rather than the laboratory environment. Listing these shortcomings regarding scientific evidence does not mean that the limitations are only attributable to natural science – indeed, improved economic information about income and price dependency for shellfish demand would improve the assessment. Our study highlights the needs for future research.

Notes

1. As a government initiative, the US government already estimates the social cost of carbon (i.e., the value of economic damage associated with a unit increase in carbon dioxide emissions) for its appraisal of government projects (Interagency Working Group on Social Cost of Carbon 2013).
2. For example, according to the FAO statistics, the European share of global aquaculture production of molluscs was 9% in 2010.
3. To be sure, capture and aquaculture fisheries involve various secondary activities such as seafood processing and may also create employment in such sectors. According to one estimate, the employment of one person in capture or aquaculture work creates an average of four jobs in secondary industry sectors (FAO, 2008: as cited by Hilmi *et al*. 2014). However, the macroeconomic impact of fishery-related employment would be small, even when including these secondary activities.
4. http://www.fao.org/fishery/statistics/en

5. The FAO data-set contains another category of molluscs: freshwater molluscs. We excluded this category from our analysis because it is not clear whether ocean acidification has any effect on freshwater organisms.
6. http://www.seaaroundus.org/
7. Cephalopods (octopuses, squids, etc.) are excluded from this category.
8. The supply elasticity is 0.2 for Eastern European and former Soviet Union countries and 0.4 for Western European countries. The demand elasticity is 1.01 for former Soviet Union countries, 0.97 for Eastern European countries and 0.91 for Western European countries.
9. The pH levels of European waters show some regional heterogeneity (see Figure 1.1 in the Appendix), but because of the limited information of the meta study on biological impact, the following analysis does not reflect the different levels of pH change across different areas.
10. The income elasticity is 0.55 for former Soviet Union countries, 0.45 for Eastern European countries and 0.35 for Western European countries.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Armstrong, C.W., S. Holen, S. Navrud, and I. Seifert. 2012. *The Economics of Ocean Acidification: A Scoping Study*. Tromsø: Fram Centre. http://www.surfaceoa.org.uk/?p=1570

Billé, R., R. Kelly, A. Biastoch, E. Harrould-Kolieb, D. Herr, F. Joos, K. Kroeker, D. Laffoley, A. Oschlies, and J.-P. Gattuso. 2013. “Taking Action Against Ocean Acidification: A Review of Management and Policy Options.” *Environmental Management* 52: 761−779.

Brander, L.M., K. Rehdanz, R.S.J. Tol, and P. van Beukering. 2012. “The Economic Impact of Ocean Acidification on Coral Reefs.” *Climate Change Economics* 3 (1): 1250002.

Brander, L.M., D. Narita, K. Rehdanz, and R.S.J. Tol. 2014. “The Economic Impacts of Ocean Acidification.” In *Handbook on the Economics of Ecosystem Services and Biodiversity*, edited by P.A.L.D. Nunes, P. Kumar, and T. Dedeurwaerdere, 78−92. Cheltenham: Edward Elgar.

Caldeira, K., and M.E. Wickett. 2003. “Anthropogenic Carbon and Ocean pH.” *Nature* 425: 365.

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

Cooley, S.R., and S.C. Doney. 2009. “Anticipating Ocean Acidification’s Economic Consequences for Commercial Fisheries.” *Environmental Research Letters* 4: 024007.

Cooley, S.R., N. Lucey, H. Kite-Powell, and S.C. Doney. 2012. “Nutrition and Income from Molluscs Today Imply Vulnerability to OA Tomorrow.” *Fish and Fisheries* 13 (2): 182−215.

Doney, S.C., V.J. Fabry, R.A. Feely and J.A. Kleypas. 2009. “Ocean Acidification: The Other CO_2 Problem.” *Annual Review of Marine Science* 1: 169−192.

Ekstrom, J.A., L. Suatoni, S.R. Cooley, L.H. Pendleton, G.G. Waldbusser, J.E. Cinner, J. Ritter, *et al.* 2015. “Vulnerability and Adaptation of US Shellfisheries to Ocean Acidification.” *Nature Climate Change* 5: 207−214.

European Commission Joint Research Centre. 2013. *The Economic Performance of the EU, Aquaculture Sector*. Luxembourg: Publications Office of the European Union.

Gaffin, S., C. Rosenzweig, X. Xing, and G. Yetman. 2004. “Downscaling and Geo-Spatial Gridding of Socio-Economic Projections from the IPCC Special Report on Emissions Scenarios (SRES).” *Global Environmental Change* 14 (2): 105−123.

Hendriks, I.E., C.M. Duarte, and M. Álvarez. 2010. “Vulnerability of Marine Biodiversity to Ocean Acidification: A Meta-Analysis, Estuarine.” *Coastal and Shelf Science* 86 (2): 157−164.

Hilmi , N., D. Allemand, S. Dupont, A. Safa, G. Haraldsson, P.A.L.D. Nunes, C. Moore, *et al.* 2013. “Towards Improved Socio-Economic Assessments of Ocean Acidification’s Impacts.” *Marine Biology* 160: 1773−1787.

Hilmi, N., D. Allemand, M. Cinar, S. Cooley, J. Hall-Spencer, G. Haraldsson, C. Hattam, *et al.* 2014. “Sensitivity of Mediterranean Countries to Ocean Acidification.” *Water* 6: 1719−1744. doi:10.3390/w6061719.

Interagency Working Group on Social Cost of Carbon. 2013. Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866.

Intergovernmental Panel on Climate Change (IPCC). 2011. Workshop Report of the *IPCC Workshop on Impacts of Ocean Acidification on Marine Biology and Ecosystems*, edited by Field, C.B., V. Barros, T.F. Stocker, D. Qin, K.J. Mach, G.-K. Plattner, M.D. Mastrandrea, M. Tignor, and K.L. Ebi, 164. Stanford, CA: IPCC Working Group II Technical Support Unit, Carnegie Institution.

Intergovernmental Panel on Climate Change (IPCC). 2014. Climate Change 2014: Impacts, Adaptation and Vulnerability.

Kroeker, K.J., R.L. Kordas, R.N. Crim, and G.G. Singh. 2010. “Meta-Analysis Reveals Negative yet Variable Effects of Ocean Acidification on Marine Organisms.” *Ecology Letters* 13 (11): 1419−1434.

Kroeker, K.J., R.L. Kordas, R. Crim, I.E. Hendriks, L. Ramajo, G.S. Singh, C.M. Duarte, and J.-P. Gattuso. 2013. “Impacts of Ocean Acidification on Marine Organisms: Quantifying Sensitivities and Interaction with Warming.” *Global Change Biology* 19: 1884−1896.

Moore, C. 2015. “Welfare Estimates of Avoided Ocean Acidification in the U.S. Mollusk Market.” *Journal of Agricultural and Resource Economics* 40 (1): 50−62.

Narita, D., K. Rehdanz, and R.S.J. Tol. 2012. “Economic Costs of Ocean Acidification: A look into the Impacts on Global Shellfish Production.” *Climatic Change* 113: 1049−1063.

Riahi, K., S. Rao, V. Krey, C. Cho, V. Chirkov, G. Fischer, G. Kindermann, N. Nakicenovic, and P. Rafaj. 2011. “RCP 8.5 − A Scenario of Comparatively High Greenhouse Gas Emissions.” *Climatic Change* 109: 33−57.

Secretariat of the Convention on Biological Diversity. 2014. “An Updated Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity, CBD Technical Series No. 75.”

Tol, R.S.J. 2009. “The Economic Effects of Climate Change.” *Journal of Economic Perspectives* 23 (2): 29−51.

Tol, R.S J. 2014. “Correction and Update: The Economic Effects of Climate Change.” *Journal of Economic Perspectives* 28 (2): 221−26.

van Vuuren, D.P., P.L. Lucas, and H. Hilderink. 2007. “Downscaling Drivers of Global Environmental Change: Enabling use of Global SRES Scenarios at the National and Grid Levels.” *Global Environmental Change* 17: 114−130.

Williamson, P., and C. Turley. 2012. “Ocean Acidification in a Geoengineering Context.” *Philosophical Transactions of the Royal Society A* 370: 4317−4342.

Wittmann, A.C., and H.-O. Pörtner. 2013. “Sensitivities of Extant Animal Taxa to Ocean Acidification.” *Nature Climate Change* 3: 995−1001.

Appendix

Table 1.1. Employment in sub-sectors of fisheries in European countries (number of workers in full-time equivalent, or FTE).

Country	Capture fisheries (total)	Processing (secondary employment of fisheries)	Aquaculture	Shellfish aquaculture	Note
Albania	5,200	800	ND	ND	FAO 2002 data
Belgium	342	ND	ND	ND	
Bulgaria	1,668	317	270	ND	
Croatia	3,720	ND	ND	ND	FAO 2008 data
Denmark	1,661	3,235	299	2	
France	7,447	15,662	10,658	9,142	
Germany	1,258	6,509	1,000[2]	17	
Greece	30,196	2,265	5,559[2]	ND	Capture figure is from FAO
Iceland	4,300	3,100[1]	ND	0	FAO 2008 data
Ireland	3,166	2,829	958	765	
Italy	20,599	5,517	2,116	1,812	
Lithuania	575	3,699	0	0	
Montenegro	159	17	36	0	
Netherlands	1,768	2,537	255	255	
Norway	9,640	32,350[1]	3,930	ND	FAO 2008 data
Portugal	17,188	6,913	1,749	1,425	
Romania	28	1,178	1,047	0	
Slovenia	77	351	28	15	
Spain	32,194	17,702	6,639	4,159	
Sweden	974	1,837	263	21	
Ukraine	31,000	10,000[1]	12,000	ND	FAO 2001 data
United Kingdom	7,192	18,572	2,671	ND	

Note: Data sources: Unless otherwise noted, the data are the 2011 figures from the Annual Economic Report on the EU Fishing Fleet, the Economic Performance of the EU Fish Processing Industry, and the Economic Performance of the EU Aquaculture Sector.

[1] Including other forms of secondary employment (distributions, etc.).

[2] In number (not in FTE).

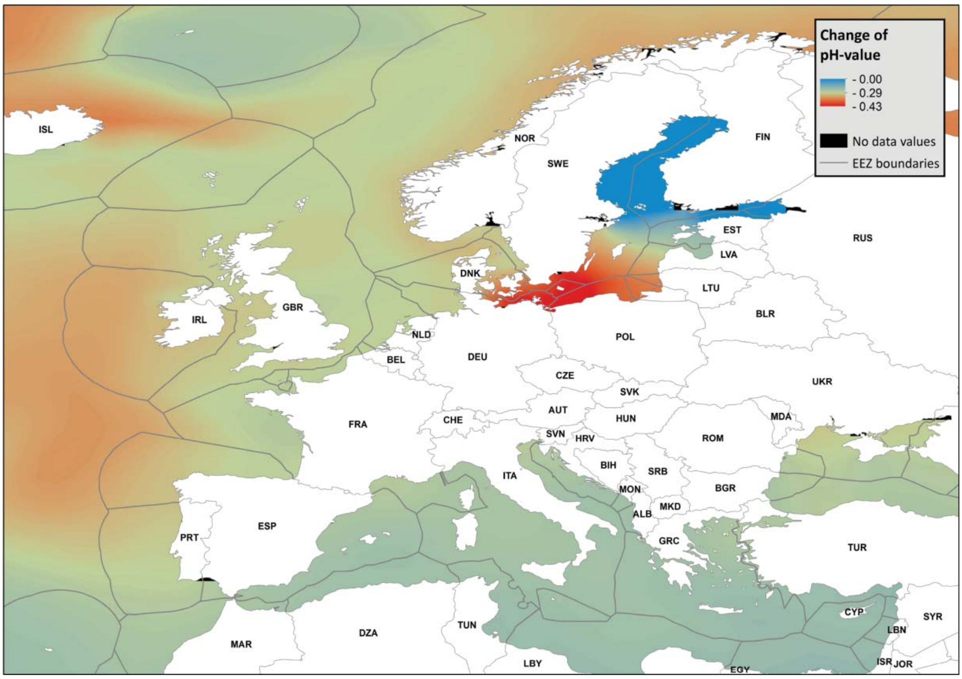

Figure 1.1. Change of pH-value between 1990−2009 and 2080−2099 (RCP 8.5). See online colour version for full interpretation.

Note: The projected pH-changes in European waters for the RCP 8.5 scenario was simulated by fully coupled Earth System Models for CMIP5/AR5. We averaged over the model output and interpolated to a 1/8 × 1/8 degree grid level (originally 1 × 1 degree grid level). Since the land mask differs for different models, the number of data points differs across grid cells.

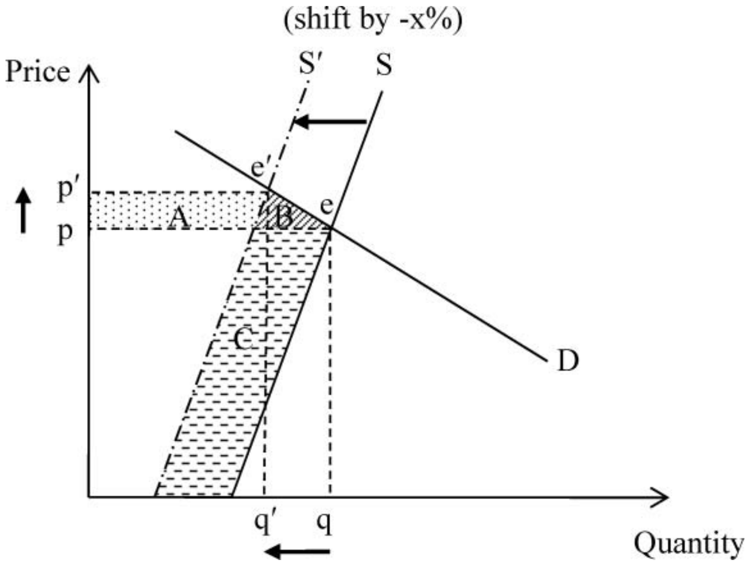

Figure 1.2. Changes in producer and consumer surpluses considered in analysis. The graph illustrates the demand and supply curves of mollusc production. The equilibrium point (e) of mollusc production without acidification is located at the intersection of the demand (D) and supply (S) curves. The slopes of the supply and demand curves can be numerically determined by using the empirical assessments of supply and demand elasticities of molluscs. Introduced as an exogenous shock, acidification raises the unit production costs of mollusc production and shifts the supply curve to the left (S → S′). The producers offset a part of the revenue loss from the increase of unit production costs by raising the price (p → p′). As a result, the equilibrium point moves from e to e′. The effective costs of ocean acidification for the consumers are the combination of costs from the loss in the consumed quantity (q → q′) and the increase in the price. C−A in the graph represents the loss of producer surplus due to acidification, whereas A+B corresponds to the loss of consumer surplus. The net total loss for the economy is B+C. The same analytical approach has been used by Narita, Rehdanz, and Tol (2012).