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Economic costs of ocean acidification: a look into the impacts on global shellfish production

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Abstract Ocean acidification is increasingly recognized as a major global problem. Yet economic assessments of its effects are currently almost absent. Unlike most other marine organisms, mollusks, which have significant commercial value worldwide, have relatively solid scientific evidence of biological impact of acidification and allow us to make such an economic evaluation. By performing a partial-equilibrium analysis, we estimate global and regional economic costs of production loss of mollusks due to ocean acidification. Our results show that the costs for the world as a whole could be over 100 billion USD with an assumption of increasing demand of mollusks with expected income growths combined with a business-as-usual emission trend towards the year 2100. The major determinants of cost levels are the impacts on the Chinese production, which is dominant in the world, and the expected demand increase of mollusks in today's developing countries, which include China, in accordance with their future income rise. Our results have direct implications for

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climate policy. Because the ocean acidifies faster than the atmosphere warms, the acidification effects on mollusks would raise the social cost of carbon more strongly than the estimated damage adds to the damage costs of climate change.

1 Introduction

Human emissions of carbon dioxide (CO_2) cause acidification of the ocean as well as climate change. While research on various aspects of climate change has generated an enormous number of studies, ocean acidification has only recently been recognized as a problem. This new recognition is giving rise to an increasing number of studies on ecological impacts of ocean acidification (reviewed by Doney et al. 2009), but estimates of economic impacts are still almost absent.

Since the acidification of ocean water is primarily driven by the well-known law of chemical equilibrium of CO_2 and water, the initial impact of ocean acidification is relatively clear (Caldeira and Wickett 2003, 2005). However, the eventual impact depends on the complex interaction of many species. This fact limits the scope for the estimation of economic consequences. Along with coral reefs (Brander et al. 2009), however, shellfish, in particular, mollusks,[1] are an exception in that the impact of ocean acidification is relatively better understood. The relative wealth of scientific research on this group is partly due to the ease of examining them in a controlled laboratory experiment and the additional interest in the calcification response of these organisms. Analysis of mollusk production is also relatively tractable because of their low trophic level on the food web. It is for this reason that we focus our analysis on this group of shellfish.

An impact assessment of mollusks under ocean acidification has a significant commercial implication in itself, as the value of marine mollusks (excluding cephalopods) produced worldwide amounts to around 15 billion USD in 2006, 9% of the world total fishery production in value terms (FAO 2008). On a volume basis, the production of marine mollusks constitutes 12% of total fishery production in the USA, 15% in EU 15, and 20% in China in 2006 (FAO 2008). At present, however, such analyses are non-existent except for Cooley and Doney (2009), who discuss the issue only in the US context.

In fact, estimation of economic impacts of ocean acidification on mollusk production would provide initial hints for economic assessment of ocean acidification in general, as well as more broadly, for economic assessment of climate change. Major assessments of the economic impact of climate change (e.g., Tol 2002; Stern 2006; Nordhaus 2008) omit ocean acidification altogether.

This study is an initial attempt to fill the research gap by performing an economic assessment of global effects of ocean acidification on mollusks by using the framework of a partial-equilibrium analysis. We estimate global and regional economic costs of production loss of mollusks due to ocean acidification in 2100 under a business-as-usual scenario. Our results show that the costs could amount to around 6 billion USD even with an assumption of constant demand of mollusks towards the future and could be over 100 billion USD with an assumption of increasing demand of mollusks with expected income growths. The major determinants of cost levels are the impacts on the Chinese production, which is currently dominant in the world, and the expected demand increase of mollusks in today's developing countries, which include China, in accordance with their future income rise. Excluding

[1] The Oxford Dictionary of English (2nd ed.) defines shellfish as "an aquatic shelled mollusk (e.g., an oyster or cockle) or a crustacean (e.g., a crab or shrimp), especially one that is edible."

China, the global estimates become around 2 billion USD under the constant demand assumption and around 15 billion USD with a demand increase. Our analysis also indicates that in key regions such as China and the USA, the economic costs are roughly evenly divided between producers and consumers, implying that the sectoral impact of acidification in the fishery industry could be acute with the limited capacity to offset the change in supply costs by price increase.

The paper is organized as follows. Section 2 briefly summarizes scientific facts of ocean acidification that serve as the basis for our analysis. Section 3 presents our approach of partial-equilibrium analysis. Section 4 describes the data that we use as the basis of our analysis. Section 5 shows results. Section 6 concludes.

2 Ocean acidification and mollusks: a note on scientific mechanisms

CO_2 emissions by humans not only increase the atmospheric concentrations of CO_2 but also alter the carbonate chemistry of the ocean, which absorbs nearly half of the total emissions to date from fossil fuel combustion and cement manufacturing (Sabine et al. 2004). Enhanced CO_2 in the atmosphere elevates the acidity of surface seawater (i.e., $[H^+]$) and decreases the concentration of carbonate ions ($[CO_3^{2-}]$) through the following series of chemical reactions:

$$CO_2(\text{atmos}) \leftrightarrow CO_2(\text{aq}) + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-} \quad (1)$$

Reflecting on that fact, there is a growing concern about ocean acidification as a major accompanying effect of global climate change. The actual levels of seawater pH exhibit some variations across spatial locations as well as by depth, reflecting different levels of physical determinants of CO_2 solubility (e.g., temperatures) and strengths of ocean circulations and biogeochemical processes. However, as atmospheric CO_2 is essentially uniform over the world, the general tendency of acidification of surface seawater is likely to be observed on a global scale. In fact, the global nature of ocean acidification is confirmed by various ocean circulation models (Orr et al. 2005). Following the business-as-usual CO_2 emission path, pH of surface seawater, whose original level is ~8.1 (weakly basic), would be reduced by 0.3–0.4 by the end of the 21st century (Caldeira and Wickett 2003, 2005; Doney et al. 2009). Combined with local patterns of ocean circulations, the level of acidification could be even much more serious in specific areas—in fact, there is an indication that upwelling of acidified water are already observed in some areas on the North American West Coast even at the current level of global CO_2 (Feely et al. 2008). Especially in productive coastal habitats, which are the primary locations for bivalve mollusk (e.g. mussels, oysters) production, the marine carbonate system is much more variable than in the open oceans, with pH values significantly lower than 8.0 already today (e.g. Burnett 1997). Future changes in seawater partial pressure of CO_2 (pCO_2) will be especially strong in these habitats (Thomsen et al. 2010).

It is easy to speculate that ocean acidification has broad implications for the functions of marine ecosystems by physically harming individuals of various marine organisms and also disrupting the balance of food webs. However, precise estimation of those effects is not simple because of the complexity of marine biology. Research is still limited on this issue, but a relatively established fact among the findings is that ocean acidification should have negative effects on the growth of some calcifiers including mollusks and corals (Kroeker et al. 2010). The chemical equilibria (1) suggest that acidification of water (i.e., high $[H^+]$) reduces the concentrations of carbonate ions ($[CO_3^{2-}]$) through the far-right reaction. Growth of mollusks' shells, which are composed of calcium carbonate ($CaCO_3$), may be hampered because a low level of carbonate ions results in dissolution of calcium carbonate through the following reaction:

$$CaCO_3 \leftrightarrow {CO_3}^{2-} + Ca^{2+} \tag{2}$$

In fact, the solubility of calcium carbonate depends on its crystal form as well. The solubility is associated with the level of the following saturation state Ω:

$$\Omega = \left[Ca^{2+}\right]\left[{CO_3}^{2-}\right]/K'_{sp} \tag{3}$$

where the solubility product K'_{sp} depend on the crystal forms of $CaCO_3$.[2] Negative effects on calcification are expected to be high for species whose shell is made of aragonite, which is a relatively unstable crystal form of calcium carbonate, although to a lesser extent, effects could also be significant for species whose shell is made of calcite, which is a relatively more stable crystal form. This is particularly problematic for mollusks with a shell that is not covered by protective organic outer layers, such as pteropods (Lischka et al. 2011). Organic coating allows bivalve mollusks to calcify even in ocean regions that are under saturated with respect to calcium carbonate (e.g. Tunnicliffe et al. 2009; Ries et al. 2009 or 2010; Thomsen et al. 2010).

A meta-analysis by Kroeker et al. (2010) indicates that negative effects of ocean acidification on the survival and growth of mollusks could become visible by the end of the 21st century under a standard scenario of climate change (IS92a), and that the negative effects are stronger on earlier developmental stages. It is also important to note, that responses even of closely related bivalve molluscs (the genus Mytilus, i.e. mussels) vary strongly between studies, with large negative effects in short-term studies (days, e.g. Gazeau et al. 2007) and less dramatic effects in studies that allowed for significant physiological acclimation time (several weeks) and high nutrient supply (Michaelidis et al. 2005; Thomsen et al. 2010). Meanwhile, the above mentioned meta-analysis shows that under the same assumptions, negative effects are much less clear for the crustaceans, the other group of shellfish. However, adaptation processes may significantly reduce vulnerability to future climate change. Despite an increasing abundance of scientific data on species performance under elevated seawater pCO_2 conditions, it needs to be noted that to date, studies that account for genetic adaptation potential of species towards elevated pCO_2 are largely missing. The few studies that exist revealed a potential for adaptation to elevated CO_2 (for an overview see Sunday et al. 2011).

Mollusks have a high commercial value as food and are an important source of protein for human consumption, especially for the populations of developing countries (Dey et al. 2008). Mollusks are produced both by capture and aquaculture. Capture fisheries, which are mainly performed in coastal environments, might be directly affected by ocean acidification. Meanwhile, aquaculture could in principle insulate itself from the acidified marine environment and be operated under controlled acidity by means of, for example, buffering with sodium bicarbonate. However, as bivalve mollusks are often fed with planktonic organisms, which are prevalent in seawater, practices of mollusk aquaculture generally involve some period of culture in open water whose acidity is impossible to be manipulated. Furthermore, in many cases, juvenile bivalve mollusks are collected from the natural ocean environment because hatchery production is often not economical, especially in developing countries (Pillay and Kutty 2005).

[2] Without any external protective mechanism (e.g., coating), dissolution occurs when $\Omega<1$.

3 Analytical approach: a partial-equilibrium model

We estimate economic costs of reduced mollusk production due to acidification by using a partial-equilibrium framework. This approach allows us to capture two factors associated with the production damage due to ocean acidification, that is, the welfare losses due to reduced production and consumption, and the welfare effects of price increase under tightening supply. As the mollusk fisheries represent only a small proportion of the entire economy (15 billion USD of annual production as opposed to 49 trillion USD of the world GDP in 2006), this simple analytical approach should offer a valid first approximation of economic impacts.

Figure 1 illustrates the demand and supply curves of mollusk production. The equilibrium point (*e*) of mollusk production without acidification is located at the intersection of the demand (*D*) and supply (*S*) curves. The slopes of the supply and demand curves could be numerically determined by using empirical assessments of supply and demand elasticities of mollusks. Introduced as an exogenous shock, acidification raises the unit production costs of mollusk production and shifts the supply curve leftward ($S \rightarrow S'$). The producers offset a part of revenue loss from the increase of unit production costs by raising the price ($p \rightarrow p'$). As a result, the equilibrium point moves from e to e'. Effective costs of ocean acidification for the consumers are the combination of costs from the loss in the consumed quantity ($q \rightarrow q'$) 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*.

Our analytical approach has an advantage over the simple multiplication method of the harvest loss rate and the baseline production value (see e.g. Cooley and Doney) in the capacity to assess the impact of price increase accompanying the change in supply costs of mollusks under ocean acidification. Indeed, with a substantial expected change of supply under ocean acidification, the effect of price adjustment would not be negligible. On the other hand, our framework does not take account of some less direct effects, such as

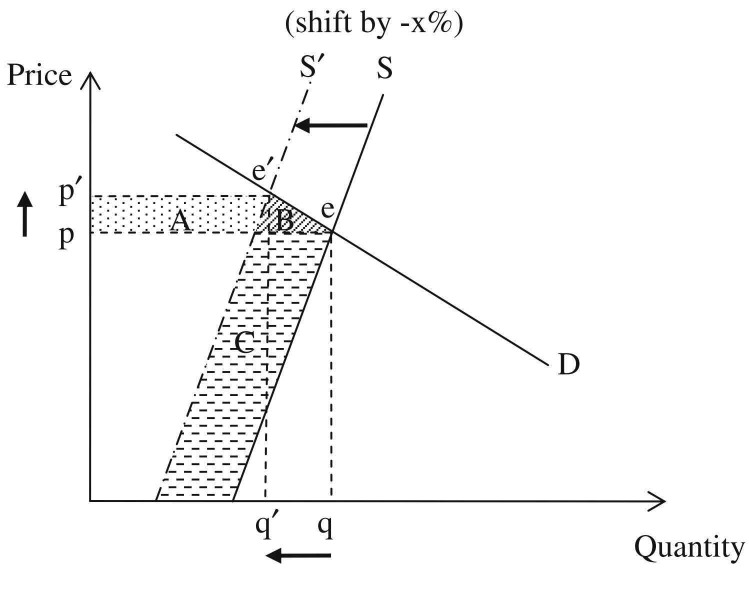


Fig. 1 Demand and supply curves of mollusks

the general-equilibrium effects of supply change on the entire domestic or world economy.

4 Data

The areas *A*, *B* and *C* in Fig. 1 could be quantitatively estimated by using empirical data of mollusk production (consumption), of the demand and supply elasticities, of the effects of acidification on the development of mollusk individuals, and of the scale of ocean acidification concurrent with climate change. Below, we describe the empirical base data used for our analysis.

For information on the relationship between ocean acidification and reduced harvest of mollusks, we use the data of Kroeker et al.'s (2010) meta-analysis on effects of acidification on marine organisms.[3] Following Kroeker et al., we consider the effect of acidification under the climate conditions in the year 2100 based on the IPCC IS92a business-as-usual scenario (which they assume is associated with a 0.4-unit decrease in pH). This relatively long time horizon, which is a reflection of the current availability of experimental data, poses limitation in practical relevance of economic loss estimation for near-term fishery management, while it still has immediate relevancy for policy making about greenhouse gas emission reduction. As for the relationship between the biological impact of lower pH water on mollusks and the harvest loss, we primarily adopt an assumption in line with Cooley and Doney's (2009), which sets the rate of harvest loss of shellfish equal to the decrease in calcification rate due to ocean acidification.[4] The rate of harvest loss corresponds to the shifting rate of the supply curve in our partial-equilibrium framework (i.e., x in Fig. 1). Kroeker et al. estimate the mean effect of acidification on the calcification rate of mollusks, which is equivalent to 43% loss from the baseline with a 95% confidence interval of 0%–65% (calculated from 9 experiments). [5] Meanwhile, as alternative proxy, we also use the survival rate of mollusks under acidification. Kroeker et al. report the mean effect of acidification on survival of mollusks (calculated from 17 experiments), which is equivalent to 35% loss from the baseline with a 95% confidence interval of 0%–62%.

It should be noted that in either case of using the calcification or survival loss as proxy, there are factors leading the assessment to both overestimation and underestimation: on the one hand, a loss in calcification or survival might not result in an equivalent commercial loss (e.g., mollusks with thinner shells might still have commercial value); on the other hand, the actual effect of acidification could be greater than implied by each individual rate because the actual effect experienced by the producers is a combination of *both* calcification and survival losses.

[3] Hendriks et al. (2010) also offer a meta-analysis of ocean acidification impacts. However, Kroeker et al. point out that Hendriks et al. do not use the standard methods of meta-analysis, which standardize studies for precision, account for variation between studies, and test for heterogeneity in effect sizes. Still, as for calcification by bivalves (a group of mollusks), Hendriks et al.'s estimates also show strong negative effects of ocean acidification in the future.

[4] Despite the use of the same proxy for acidification damage, their estimates are significantly different from ours as they base their analysis on a different study published earlier (Gazeau et al. 2007: the loss rate is 10–25%).

[5] They report their results in the following ln-transformed response ratio$LnRR = \ln(R) = \ln\left(\overline{X}_E\right) - \ln\left(\overline{X}_C\right)$, where X_E, $X_C$are the mean response in the experimental and control treatments, respectively. We use numbers converted from logarithmic rates into percentages, whose conversion is made by ourselves.

Mollusks are produced both through capture fisheries and aquaculture. As we noted in Section 2, there is a strong reason to assume that not only capture fisheries but also aquaculture of mollusks is affected by acidification. In this analysis, we simply assume that the effect of acidification equally falls on capture fisheries and aquaculture.

As for production quantities of mollusks, we base our estimates on data provided by the FAO Fisheries and Aquaculture Department[6] and by the Sea Around Us Project. [7] Annual information on total aquaculture and capture production by country is obtained for the period 1997–2006. The FAO database contains data of aquaculture production in value (in USD) by country and species. Our aquaculture dataset covers 134 gastropod and bivalve species belonging to the following five species groups: “abalones, winkles and conches,” “oysters,” “mussels,” “scallops and pectinids,” and “clams, cockles, and arkshells.”[8] Meanwhile, the FAO database does not include data on capture production in value (it has only volume data). To supplement the FAO data we use data from the Sea Around Us database. The database provides landing value data for an aggregate category “molluscs” [9] whose capture takes place within the exclusive economic zones (EEZ) of individual countries. All value data used in the analysis are normalized in 2000 USD.

We aggregate the country-level production data by region by using the regional categories of the IMPACT model. [10] IMPACT is a global simulation model to examine food supply, demand, trade, prices, and food security and is the only available model that incorporates a globally consistent set of elasticity parameters regarding the mollusk fisheries. The model has been used by a number of peer-reviewed academic studies (e.g., Rosegrant and Cline 2003). An application of the model to global analysis of fisheries and the economy is Delgado et al. (2003). In the following, we mainly discuss the ten regions and countries, which constitute the current major producers of marine mollusks: USA, EU15, Japan, Australia, Other Developed Countries, [11] Mexico, Turkey, Viet Nam, China, and South Korea. In Table 1 information is provided on GDP (nominal and PPP), population, and production volumes of total fisheries and mollusks by aquaculture and capture for those selected ten regions and the entire world.

For data of future economic conditions, we utilize GDP projections to the year 2100 based on IPCC’s A1B scenario, as the scenario corresponds to almost an identical level of atmospheric CO_2 concentrations (around 710 ppm) to that of the old IS92a scenario (IPCC 2001, WG I report Annex II; see also Caldeira and Wickett 2005). Country-level GDP values that we use in our analysis are those disaggregated by Gaffin et al. (2004) and van Vuuren et al. (2007) from A1B scenario, which are the only two available datasets of national-level GDP projections consistent with the IPCC scenario. Meanwhile, we adopt

[6] http://www.fao.org/fishery/statistics/en

[7] http://www.seaaroundus.org/data/

[8] The FAO dataset contains another category of mollusks, “freshwater mollusks.” We excluded this category from our analysis because it is not clear whether ocean acidification could cause any effect on freshwater organisms.

[9] Cephalopods (octopuses, squids, etc.) are excluded from this category.

[10] In total there are 37 regions. IMPACT regional categories omit a number of small island nations, but the combined production quantities of mollusks from those countries are not negligible. To address this problem, we set up an additional regional category named “Other Small Island States.” The results that we present in the Appendix contain our estimates for that region as well. The following are categorized as “Other Small Island States”: American Samoa, Anguilla, Antigua and Barbuda, Cook Islands, Kiribati, New Caledonia, Palau, Samoa, Solomon Islands, St. Pierre and Miquelon, and Tonga.

[11] According to the IMPACT model this includes Canada, Iceland, Israel, Malta, New Zealand, Norway, South Africa, and Switzerland.

Table 1 Current (1997–2006 average) GDP, population and volumes of fisheries of selected 10 regions and the entire world (the nominal GDP and GDP PPP are based on the 2000 constant USD and on the 2005 constant international USD, respectively)

	GDP (10^9 USD)	GDP PPP (10^9 USD)	Population (10^6)	Capture fisheries (10^3 t)	Aquaculture (10^3 t)	Marine mollusks capture (10^3 t)	Marine mollusks aquaculture (10^3 t)	Marine mollusks capture (% of total fisheries)	Marine mollusks aquaculture (% of total fisheries)
USA	10,112	11,412	286	4,915	498	543	135	10	2.5
EU15	8,217	11,012	380	5,931	1,245	352	728	5	10.1
Japan	4,745	3,691	127	4,946	1,297	397	451	6	7.2
Australia	433	592	20	222	36	19	13	7	5.1
Other dev'd countries	1,503	2,088	99	7,026	801	132	120	2	1.5
Mexico	583	1,189	99	1,360	81	68	3	5	0.2
Turkey	282	662	68	514	80	28	1	5	0.2
Viet Nam	36	142	80	1,674	830	57	78	2	3.1
China	1,433	4,027	1,274	14,820	31,023	1,045	8,133	2	17.7
South Korea	572	944	47	1,863	887	77	267	3	9.7
World	33,128	50,906	6,193	92,041	39,503	3,188	10,436	2	7.9

the income elasticity levels of mollusk consumption[12] employed in the IMPACT model.[13] As for the demand and supply elasticities, we adopt the parameter levels used by the IMPACT model (Delgado et al. 2003).[14] Those levels are generally in agreement with various empirical estimates, such as those by Dey et al. (2008).

5 Scenarios and results

We examine a number of scenarios in our analysis. As the base case, we assess the economic costs of ocean acidification when acidification exogenously affects the current level of mollusk production, which is set at the average over 1997–2006 based on the FAO data. An implicit assumption for this case is that demand of mollusks will stay constant in the future. Alternatively, we also consider a more realistic case that the demand for mollusks becomes greater because of economic development by the time when acidification becomes significant. This factor magnifies the economic damage of ocean acidification. Economic costs are assessed as the difference between the enhanced levels of production without ocean acidification and with ocean acidification. We estimate the demand increase to 2100 by multiplying GDP projections by estimated income elasticity data of mollusk consumption.

In total we use nine different scenarios in analysis. They are coded with scenario names consisting of characters (e.g., B_T_P). Characters signify the following:

B: No income rise ("baseline")
V: Income rise according to van Vuuren et al. (2007)
G: Income rise according to Gaffin et al. (2004)

[12] Categorized as "High Value Other Aquaculture" and "High Value Other Capture" in IMPACT.
[13] Values are set region by region and lie in the range of [0.15, 0.65].
[14] Values are set region by region and lie in the ranges of [−1.11, −0.77] for the demand elasticity and of [0.2, 0.4] for the supply elasticity.

T: Aquaculture+capture ("total")
A: Aquaculture only
C: Capture only
N: Effects on consumers
P: Effects on producers

Figure 2 shows the total economic costs (i.e., producer+consumer surplus) of mollusk production loss due to ocean acidification in the ten selected regions. Estimates for other regions are found in the Appendix (this applies to all the results to be discussed in this section). The main estimates in the graph are based on the mean effect on calcification by Kroeker et al. (2010). The upper bounds of error bars correspond to their lower-bound estimate of calcification impact.

The most noticeable feature in the graph is the dominance of Chinese losses. The combined loss of aquaculture and capture without income rise (B_T) is around 4 billion USD for China, which is far greater than the second largest figure for EU 15, which is around 500 million USD. The world total costs in the B_T case are around 6 billion USD. The difference between China and developed economies is even magnified with the assumed income rise: for the cases with income rise (V_T and G_T), China, whose economy is still to grow significantly, has the loss almost one order of magnitude greater than those in other regions (note that the columns for China are scaled by 1/10 on the graph). Primarily determined by Chinese losses, the total global costs of mollusk losses with income rise are estimated to be 111 billion USD and 141 billion USD based on van Vuuren et al's projections (V_T) and Gaffin et al.'s projections (G_T), respectively.

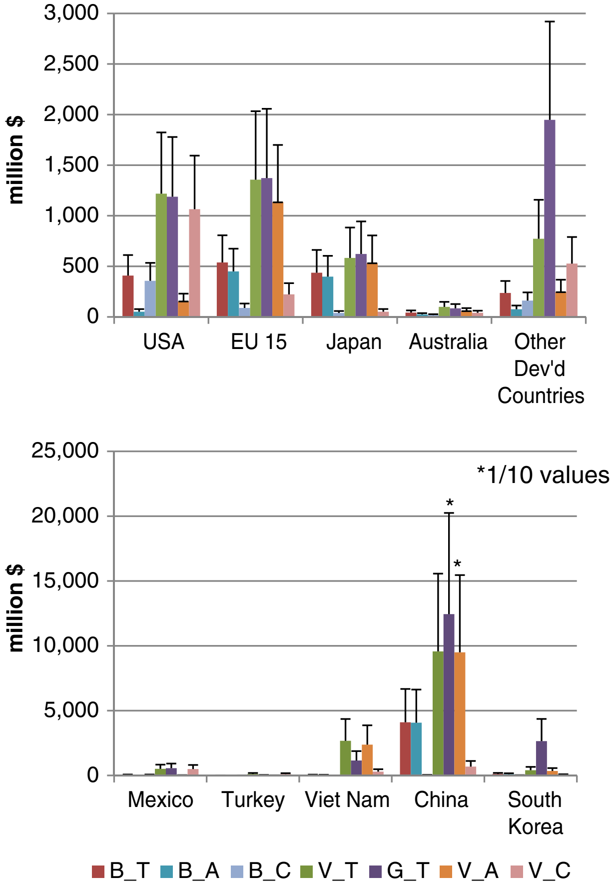
In fact, the predominant shares of China in the global estimates urge us some caution on the figures. FAO (2010) points out that the past data of Chinese fishery statistics are likely subject to significant reporting biases. Excluding the Chinese estimates, the above global figures of V_T and G_T become 15 billion USD and 16 billion USD, respectively.

When the Chinese data are taken at face value, a contrasting feature between China and USA is the balance between capture and aquaculture: dominance of aquaculture for the former and that of capture for the latter. This suggests that if China's aquaculture practices find a technical means to mitigate the impact of acidified water in the future, the Chinese losses as well as the global losses could be significantly reduced from the levels of our estimates. On the other hand, the capture-intensive US mollusk fisheries would be more likely to experience the losses of our predicted levels.

Figure 3 presents the losses of consumer and producer surplus as impact of ocean acidification on mollusk production in the ten regions for the case of constant future demand of mollusks. The losses of consumer and producer surpluses show roughly even distributions for the largest producers including China, USA, and EU15, while the consumer surplus loss is significantly higher than the producer surplus loss in Japan and South Korea. This implies that the producers in the former group of regions have only limited capacity to pass the costs of acidification onto the consumers through a price increase—hence the damage for the mollusk fishery sector might be acute. An interesting feature is that the relative losses of the producers to the consumers become large in the case of stronger acidification (see the error bars). In other words, the stronger acidification is, the greater the relative burdens on the producers become.

Figure 4 is similar to Fig. 3 but is based on GDP growth according to van Vuuren et al. (2007).[15] Patterns are similar to those of Fig. 3 for each individual region, but relative patterns across regions differ.

[15] Estimates based on Gaffin et al.'s projections show basically the same features. Estimated figures are presented in the Appendix.

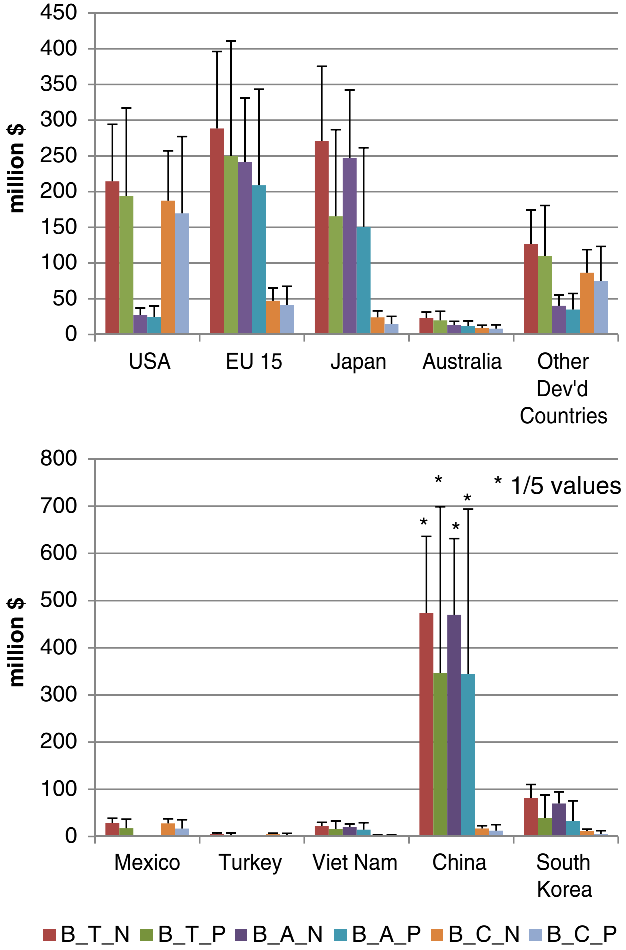


Note

The main estimates are based on the mean effect on calcification by Kroeker et al. (2010), and the upper bounds of error bars correspond to their lower-bound estimate of calcification impact.

B_T: No income rise, aquaculture + capture
B_A: No income rise, aquaculture
B_C: No income rise, capture
V_T: Income rise according to van Vuuren et al. (2007), aquaculture + capture
G_T: Income rise according to Gaffin et al. (2004), aquaculture + capture
V_A: Income rise according to van Vuuren et al. (2007), aquaculture
V_C: Income rise according to van Vuuren et al. (2007), capture

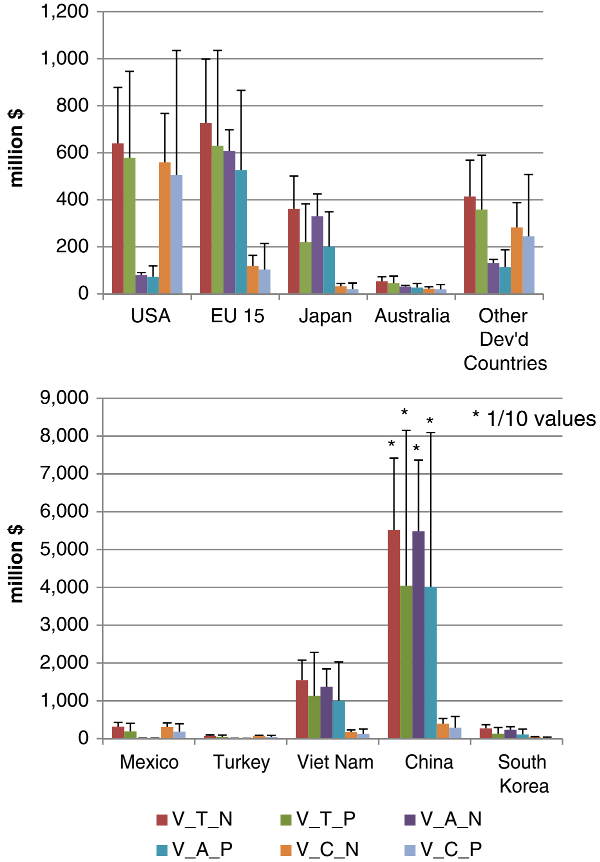
Fig. 2 Total economic costs of mollusk production loss due to ocean acidification in 10 selected regions. The main estimates are based on the mean effect on calcification by Kroeker et al. (2010), and the upper bounds of error bars correspond to their lower-bound estimate of calcification impact. B_T: No income rise, aquaculture+capture. B_A: No income rise, aquaculture. B_C: No income rise, capture. V_T: Income rise according to van Vuuren et al. (2007), aquaculture+capture. G_T: Income rise according to Gaffin et al. (2004), aquaculture+capture. V_A: Income rise according to van Vuuren et al. (2007), aquaculture. V_C: Income rise according to van Vuuren et al. (2007), capture



Note
The main estimates are based on the mean effect on calcification by Kroeker et al. (2010), and the upper bounds of error bars correspond to their lower-bound estimate of calcification impact.

B_T_N: No income rise, aquaculture + capture, consumer surplus loss
B_T_P: No income rise, aquaculture + capture, producer surplus loss
B_A_N: No income rise, aquaculture, consumer surplus loss
B_A_P: No income rise, aquaculture, producer surplus loss
B_C_N: No income rise, capture, consumer surplus loss
B_C_P: No income rise, capture, producer surplus loss

Fig. 3 Losses of consumer and producer surpluses as impact of ocean acidification on mollusk production in 10 regions, the case of constant future demand. B_T_N: No income rise, aquaculture+capture, consumer surplus loss. B_T_P: No income rise, aquaculture+capture, producer surplus loss. B_A_N: No income rise, aquaculture, consumer surplus loss. B_A_P: No income rise, aquaculture, producer surplus loss. B_C_N: No income rise, capture, consumer surplus loss. B_C_P: No income rise, capture, producer surplus loss



Note

The main estimates are based on the mean effect on calcification by Kroeker et al. (2010), and the upper bounds of error bars correspond to their lower-bound estimate of calcification impact.

V_T_N: Income rise according to van Vuuren et al. (2007), aquaculture + capture, consumer surplus loss
V_T_P: Income rise according to van Vuuren et al. (2007), aquaculture + capture, producer surplus loss
V_A_N: Income rise according to van Vuuren et al. (2007), aquaculture, consumer surplus loss
V_A_P: Income rise according to van Vuuren et al. (2007), aquaculture, producer surplus loss
V_C_N: Income rise according to van Vuuren et al. (2007), capture, consumer surplus loss
V_C_P: Income rise according to van Vuuren et al. (2007), capture, producer surplus loss

Fig. 4 Losses of consumer and producer surpluses as impact of ocean acidification on mollusk production in 10 regions, the case of increased future demand based on GDP projections by van Vuuren et al. (2007). V_T_N: Income rise according to van Vuuren et al. (2007), aquaculture+capture, consumer surplus loss. V_T_P: Income rise according to van Vuuren et al. (2007), aquaculture+capture, producer surplus loss. V_A_N: Income rise according to van Vuuren et al. (2007), aquaculture, consumer surplus loss. V_A_P: Income rise according to van Vuuren et al. (2007), aquaculture, producer surplus loss. V_C_N: Income rise according to van Vuuren et al. (2007), capture, consumer surplus loss. V_C_P: Income rise according to van Vuuren et al. (2007), capture, producer surplus loss

6 Discussion and concluding remarks

Our results show that the global economic costs of mollusk loss from ocean acidification are around 6 billion USD annually under the assumption of a constant demand of mollusks and could in fact be well over 100 billion USD if the demand for mollusks increases with future income rise. These estimates are primarily determined by the effects on the globally dominant Chinese mollusk production and a presumed rise of demand for mollusks in today's developing countries in accordance with their income growth. If China is excluded, the former becomes around 2 billion USD, and the latter is reduced to around 15 billion USD. At a regional level, our estimates for the USA, which are around 400 million USD without income rise, are significantly higher than the figures suggested by Cooley and Doney (2009) in the US context, who consider 75–187 million USD of loss in the annual revenue flow in that country. One reason for this difference is the difference in the base data. They use different data sources for production (FAO or NMFS statistics) and apply a lower estimate of harvest loss (Gazeau et al. 2007). The other reason is more conceptual: our assessment takes into account the welfare losses due to price increases, which are not captured by Cooley and Doney.

Meanwhile, the estimated economic costs amount only to a very small fraction of world GDP or the total expected economic damage of climate change. The share of the mollusk loss to the world GDP in 2100 is 0.018% based on van Vuuren et al.'s GDP projections and 0.027% based on Gaffin et al.'s GDP projections. These figures correspond to 1.0% and 1.5% of the total expected damage of climate change (the total expected damage of climate change corresponds to 1.8% of world GDP *excluding* the impacts of ocean acidification) based on the equation[16] from Tol's (2009) meta-study on the economic impact of climate change impact combined with by the estimated increase of global surface temperature by the end of the 21st century under A1B scenario (2.8°C). Estimates of the social cost of carbon would increase more than the above percentage estimates if the effect on mollusks is included, because the ocean acidifies faster than the atmosphere warms. Nonetheless, it would be fair to argue that the recognition of negative effects of ocean acidification on mollusks would not have significant bearings on the discussions of global CO_2 emission policy. However, it is of course the case that the mollusk fisheries constitute only a small fraction of total fisheries, and that the total impact of ocean acidification on fisheries could be much greater than our estimates, which exclusively examine mollusks. It should be also noted that the impacts show regional differences, reflecting the differences both in economic structure and in physical properties of the surrounding oceans, and that the relative regional impacts could be greater than the global figures suggest.

This analysis is a first attempt of a global assessment, and its scope is constrained by the availability of empirical base data. In particular, scientific assessment is still scarce as to biological impact of ocean acidification and to the interactive effects of acidification with other forms of global changes, such as the rises of ocean temperatures and the sea level, which by themselves may be greater stressors on marine organisms than acidification is. In addition, little is known about evolutionary adaption in response to ocean acidification. The few existing studies point to possibility of adaptation which would reduce the vulnerability to future climate change.

Provided that the scientific basis becomes more solid in the coming years, however, it is possible to extend the research in the following directions. First, the analysis could be fed into a general-equilibrium model, and the impacts on trade, sectoral productions and

[16] $D (\%)=2.46*(\Delta T) - 1.11*(\Delta T)^2$. See Fig. 1 of Tol (2009).

employment could be investigated—in fact, the traded (exported) volume of marine mollusks constitutes a fraction of the world marine mollusk production (23% by volume in 2006 according to FAO 2008), but our analysis does not take this factor into account. Second, this study could be combined with an ecosystem model, and broad impacts of ocean acidification on fisheries could be examined. Third, different management options for aquaculture could be investigated including e.g. the use of sodium bicarbonate (NaHCO3-) as a buffer increasing production costs. All this is deferred to future research.

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