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Economic Costs of Ocean Acidification: A Look into the Impacts on 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. 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 low-income countries, which include China, in accordance with their future income rise.

Keywords: Climate Change, Economic Impact, Mollusks, Ocean Acidification

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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 because of a relative wealth of scientific research on this group and also 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

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[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.”

mollusks in today’s low-income countries, which include China, in accordance with their future income rise. 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 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:

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

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 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. 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:

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

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:

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

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 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. 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 (an exception is Collins and Bell, 2004). Adaptation processes may significantly reduce vulnerability to future climate change.

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

Mollusks have a high commercial value as food and are an important source of protein for human consumption, especially for populations in 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).

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. 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. On the other hand, our framework does not take account of some less direct effects, such as the general-equilibrium effects of supply change on the entire domestic or world economy.

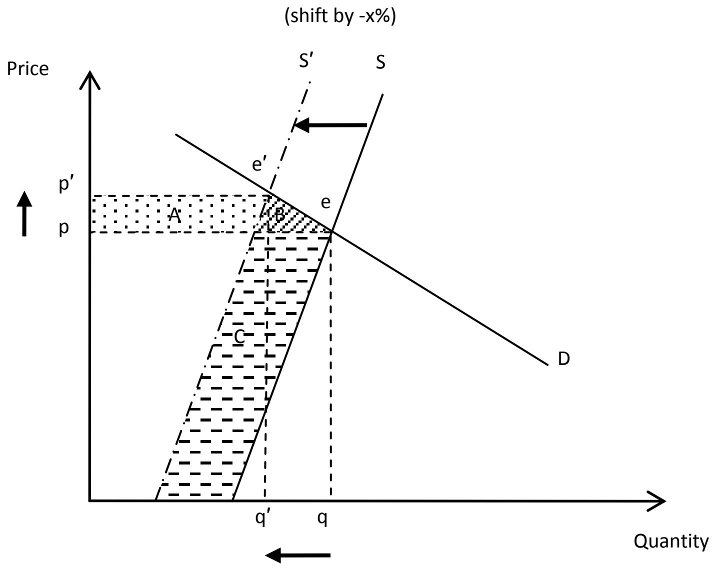

Figure 1. Demand and supply curves of mollusks

4 Data

The areas *A*, *B* and *C* in Figure 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). 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 Figure 1). Kroeker et al. estimate the mean effect of acidification on the calcification rate of mollusks, which is equivalent to 43% loss

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[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%).

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.

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 See 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.” Meanwhile, the FAO database does not include data on capture production in value (it has only volume data). Tto supplement the FAO data we use data from the See Around Us database. The database provides landing value data for an aggregate category “molluscs” [8] 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 (Delgado et al., 2003). [9] In the following, we mainly discuss the ten regions and countries, which constitute the current major producers of marine mollusks: USA, EU15, Japan,

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[5] They report their results in the following ln-transformed response ratio $LnRR = \ln(R) = \ln(\overline{X}_E) - \ln(\overline{X}_C)$, where $\overline{X}_E$, $\overline{X}_C$ 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.

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

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

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

[9] 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.

Australia, Other Developed Countries,[10] 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.

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

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 710ppm) 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. Meanwhile, we adopt the income elasticity levels of mollusk consumption[11] employed in the IMPACT model.[12] As for the demand and supply elasticities, we adopt the parameter levels used by the IMPACT model (Delgado et al., 2003).[13] Those levels are generally in agreement with various empirical estimates, such as those by Dey et al. (2008).

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[10] Canada, Iceland, Israel, Malta, New Zealand, Norway, South Africa, and Switzerland

[11] Categorized as "High Value Other Aquaculture" and "High Value Other Capture" in IMPACT

[12] Values are set region by region and lie in the range of [0.15, 0.65].

[13] 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.

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)
T: Aquaculture + capture ("total")
A: Aquaculture only
C: Capture only
C: 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 96 billion USD and 124 billion USD based on van Vuuren et al's projections (V_T) and Gaffin et al.'s projections (G_T), respectively. Meanwhile, 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 Figure 3 but is based on GDP growth according to van Vuuren et al. (2007).[14] Patterns are similar to those of Figure 3 for each individual region, but relative patterns across regions differ.

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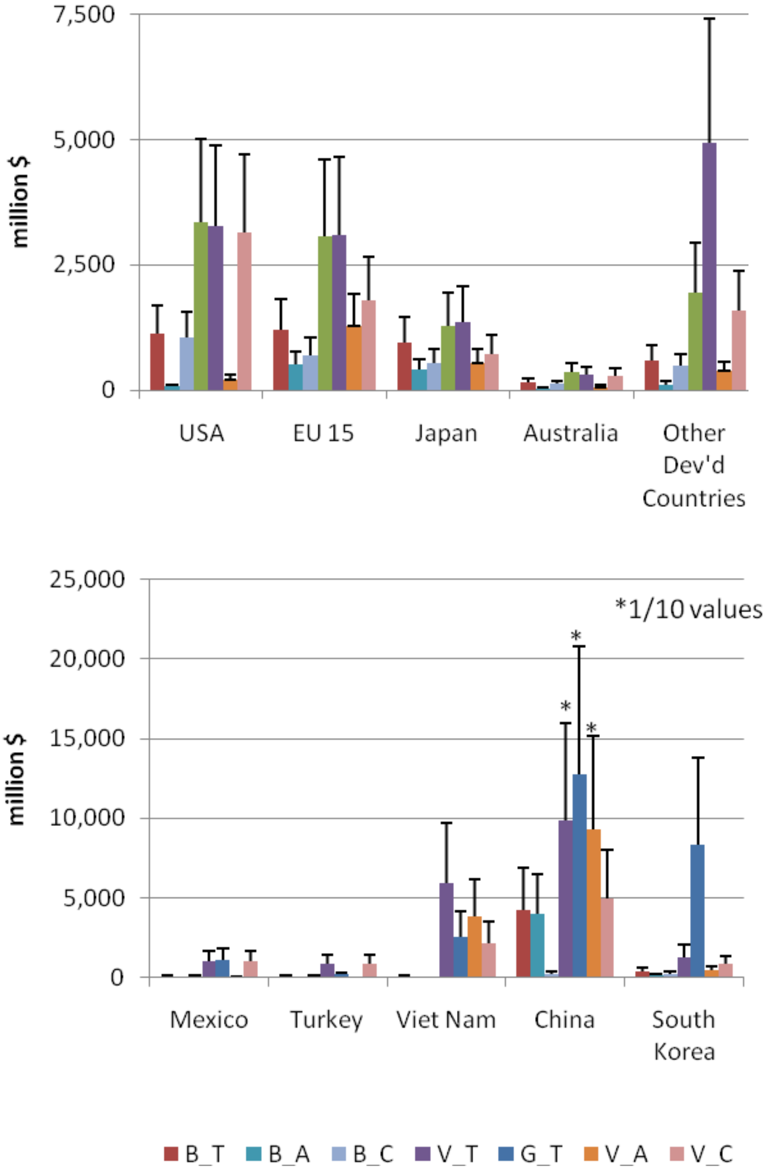
[14] Estimates based on Gaffin et al.'s projections show basically the same features. Estimated figures are presented in the Appendix.

Figure 2. Total economic costs of mollusk production loss due to ocean acidification in 10 selected regions

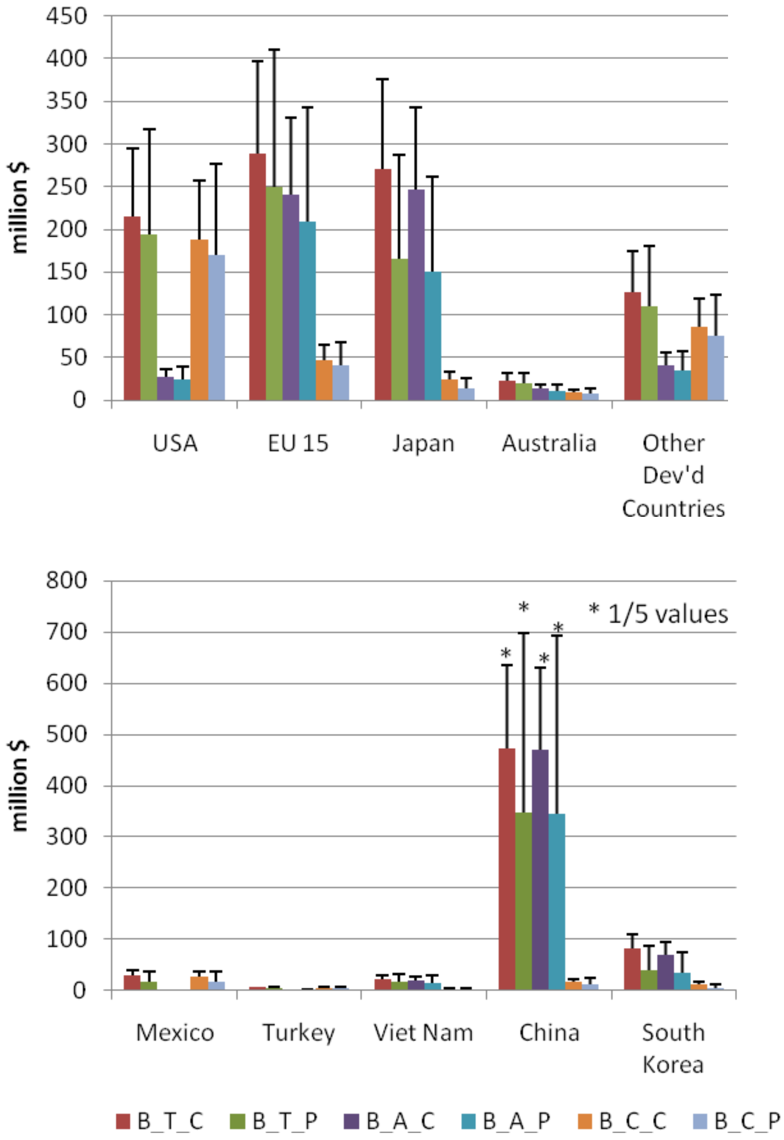


Note

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.
Developed regions (top panel) and developing regions (bottom panel).

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

Figure 3. Losses of consumer and producer surpluses as impact of ocean acidification on mollusk production in 10 regions, the case of constant future demand

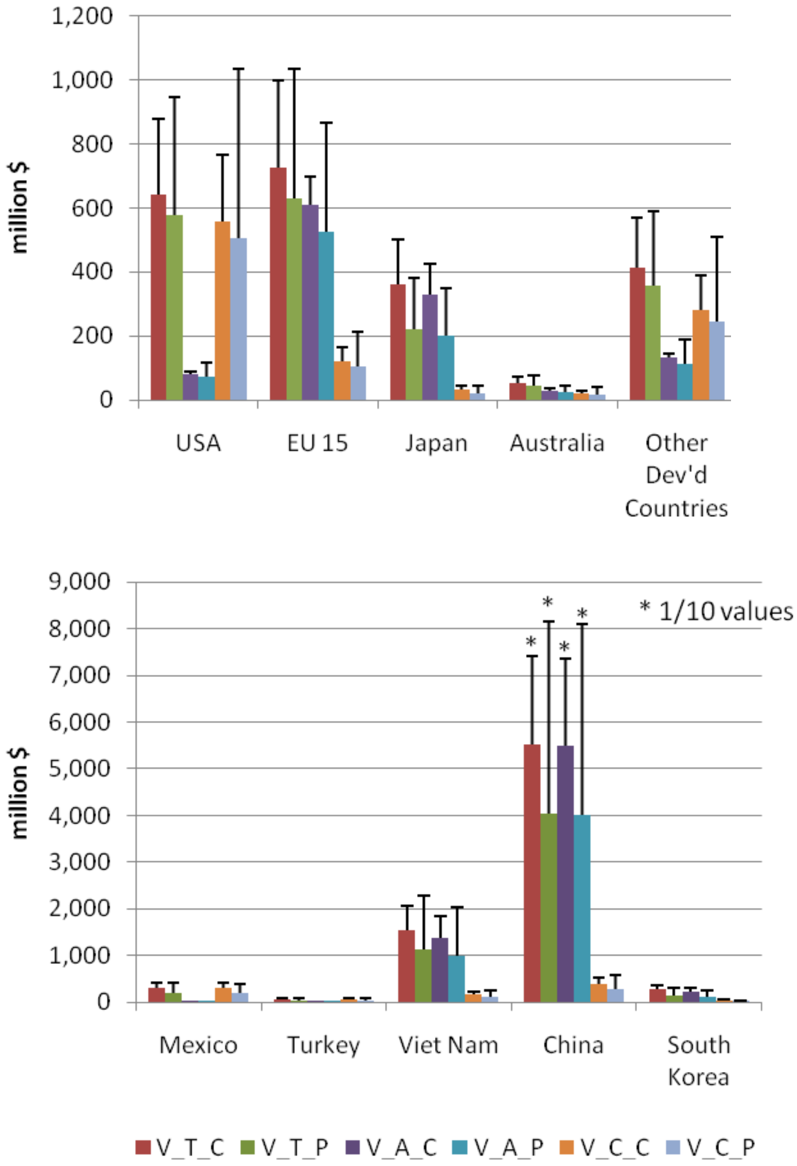


Note

Developed regions (top panel) and developing regions (bottom panel).

B_T_C: No income rise, aquaculture + capture, consumer surplus loss
B_T_P: No income rise, aquaculture + capture, producer surplus loss
B_A_C: No income rise, aquaculture, consumer surplus loss
B_A_P: No income rise, aquaculture, producer surplus loss
B_C_C: No income rise, capture, consumer surplus loss
B_C_P: No income rise, capture, producer surplus loss

Figure 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)



Note
Developed regions (top panel) and developing regions (bottom panel).

V_T_C:	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_C:	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_C:	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 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 low-income countries in accordance with their income growth. 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 (which corresponds to 1.8% of world GDP *excluding* the impacts of ocean acidification) based on the equation[15] 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 that 1.8% 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, 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, especially that of scientific assessment on biological impact of ocean acidification. 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 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.

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

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Appendix. Estimated economic costs of reduced mollusk production due to ocean acidification (losses in consumer surplus and producer surplus and the total net loss)

(a) Estimates based on the mean effect size on calcification

(unit: million USD)

Region	No income rise			Van Vuuren GDP 2100			Gaffin GDP 2100		
	-Δ[Cons. Surplus] (A+B) *B_T_C*	-Δ[Prod. Surplus] (C-A) *B_T_P*	Total net loss (A+B) *B_T*	-Δ[Cons. Surplus] (A+B) *V_T_C*	-Δ[Prod. Surplus] (C-A) *V_T_P*	Total net loss (A+B) *V_T*	-Δ[Cons. Surplus] (A+B) *G_T_C*	-Δ[Prod. Surplus] (C-A) *G_T_P*	Total net loss (A+B) *G_T*
World	**3,658**	**2,698**	**6,356**	**64,100**	**46,830**	**110,930**	**81,536**	**59,354**	**140,890**
USA	214	194	408	640	579	1,219	624	564	1,188
EU 15	288	250	538	727	630	1,357	735	637	1,372
Japan	271	165	437	362	221	583	386	236	622
Australia	23	20	43	53	46	99	45	39	85
Other Dev'd Countries	127	110	237	414	358	772	1,044	904	1,948
East. Europe	3	2	5	32	19	52	45	27	73
Central Asia	NA	NA	NA	NA	NA	NA	NA	NA	NA
Rest Former USSR	16	12	28	315	231	546	304	223	527
Mexico	29	17	46	318	193	511	350	212	562
Brazil	5	3	8	46	28	74	60	36	96
Argentina	34	21	55	254	154	408	415	251	665
Colombia	0	0	0	3	2	5	2	1	3
Other Latin Am.	116	70	186	2,066	1,250	3,317	1,311	793	2,103
Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA
Northern Sub-Saharan Africa	1	1	1	151	130	281	35	30	65
Central & Western SS Afr.	3	2	5	215	185	400	198	170	368
Southern SS Africa	0	0	0	4	4	8	2	2	4
Eastern SS Africa	NA	NA	NA	NA	NA	NA	NA	NA	NA
Egypt	0	0	0	11	7	18	4	3	7
Turkey	6	3	9	74	45	118	17	10	28
Other W. Asia N. Africa	1	1	3	62	54	116	40	34	74
India	1	0	1	30	22	51	19	14	33
Pakistan	NA	NA	NA	NA	NA	NA	NA	NA	NA
Bangladesh	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other S. Asia	0	0	0	1	1	2	0	0	0
Indonesia	11	8	18	311	228	539	358	262	620
Thailand	15	11	25	185	136	321	495	363	858
Malaysia	10	7	17	152	111	263	331	242	573
Philippines	1	1	3	57	42	99	50	36	86
Viet Nam	22	16	39	1,545	1,132	2,677	667	489	1,156
Myanmar	1	0	1	28	20	48	22	16	38
Other SE Asia	1	1	1	9	7	16	24	17	41
China	2,367	1,735	4,102	55,219	40,470	95,689	71,806	52,626	124,432
South Korea	82	39	120	273	130	403	1,794	855	2,649
Other E. Asia	11	8	19	548	401	949	326	239	564
ROW	1	1	2	17	12	29	31	23	54
Other Small Island States	1	0	1	5	4	9	20	15	35

(b) Estimates based on the mean effect size on calcification, aquaculture only

(unit: million USD)

Region	No income rise			Van Vuuren GDP 2100			Gaffin GDP 2100		
	-Δ[Cons. Surplus] (A+B) *B_A_C*	-Δ[Prod. Surplus] (C-A) *B_A_P*	Total net loss (A+B) *B_A*	-Δ[Cons. Surplus] (A+B) *V_A_C*	-Δ[Prod. Surplus] (C-A) *V_A_P*	Total net loss (A+B) *V_A*	-Δ[Cons. Surplus] (A+B) *G_A_C*	-Δ[Prod. Surplus] (C-A) *G_A_P*	Total net loss (A+B) *G_A*
World	**3,109**	**2,266**	**5,375**	**59,678**	**43,602**	**103,280**	**76,614**	**55,756**	**132,369**
USA	27	24	51	81	73	153	79	71	150
EU 15	241	209	450	608	526	1,134	615	532	1,147
Japan	247	151	398	330	201	531	352	215	567
Australia	13	12	25	31	27	58	27	23	50
Other Dev'd Countries	40	35	75	132	114	245	332	287	619
East. Europe	1	0	1	8	5	13	12	7	19
Central Asia	NA	NA	NA	NA	NA	NA	NA	NA	NA
Rest Former USSR	0	0	0	4	3	7	4	3	7
Mexico	1	1	1	10	6	16	11	7	17
Brazil	3	2	4	26	16	41	33	20	53
Argentina	0	0	0	0	0	0	0	0	1
Colombia	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Latin Am.	65	39	104	1,153	698	1,851	731	442	1,174
Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA
Northern Sub-Saharan Africa	NA	NA	NA	NA	NA	NA	NA	NA	NA
Central & Western SS Afr.	0	0	0	2	1	3	2	1	3
Southern SS Africa	0	0	0	3	3	5	1	1	3
Eastern SS Africa	NA	NA	NA	NA	NA	NA	NA	NA	NA
Egypt	NA	NA	NA	NA	NA	NA	NA	NA	NA
Turkey	1	0	1	7	4	11	2	1	3
Other W. Asia N. Africa	0	0	0	8	7	15	5	4	10
India	0	0	1	22	16	39	14	11	25
Pakistan	NA	NA	NA	NA	NA	NA	NA	NA	NA
Bangladesh	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other S. Asia	NA	NA	NA	NA	NA	NA	NA	NA	NA
Indonesia	0	0	0	1	1	2	1	1	2
Thailand	12	9	21	158	116	273	422	309	730
Malaysia	5	4	9	80	59	139	175	128	304
Philippines	1	1	2	44	32	76	38	28	66
Viet Nam	20	15	34	1,373	1,006	2,379	593	434	1,027
Myanmar	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other SE Asia	0	0	1	5	4	9	13	9	22
China	2,350	1,722	4,072	54,822	40,179	95,001	71,289	52,248	123,537
South Korea	70	33	103	234	112	346	1,540	734	2,275
Other E. Asia	11	8	18	535	392	927	318	233	551
ROW	0	0	0	1	0	1	1	1	2
Other Small Island States	0	0	0	1	1	2	4	3	7

(c) Estimates based on the mean effect size on calcification, capture only

(unit: million USD)

Region	No income rise			Van Vuuren GDP 2100			Gaffin GDP 2100		
	-Δ[Cons. Surplus] (A+B) *B_C_C*	-Δ[Prod. Surplus] (C-A) *B_C_P*	Total net loss (A+B) *B_C*	-Δ[Cons. Surplus] (A+B) *V_C_C*	-Δ[Prod. Surplus] (C-A) *V_C_P*	Total net loss (A+B) *V_C*	-Δ[Cons. Surplus] (A+B) *G_C_C*	-Δ[Prod. Surplus] (C-A) *G_C_P*	Total net loss (A+B) *G_C*
World	**549**	**432**	**981**	**4,418**	**3,226**	**7,645**	**4,921**	**3,598**	**8,518**
USA	187	170	357	559	506	1,065	545	493	1,039
EU 15	47	41	88	119	103	223	121	105	225
Japan	24	15	39	32	19	51	34	21	55
Australia	9	8	18	22	19	41	19	16	35
Other Dev'd Countries	87	75	161	282	245	527	712	617	1,329
East. Europe	2	1	4	24	15	38	34	20	54
Central Asia	NA	NA	NA	NA	NA	NA	NA	NA	NA
Rest Former USSR	16	12	28	311	228	539	300	220	520
Mexico	28	17	45	308	187	495	339	205	545
Brazil	2	1	3	20	12	33	26	16	42
Argentina	34	21	55	254	154	408	414	250	665
Colombia	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Latin Am.	51	31	82	913	553	1,466	579	350	930
Nigeria	0	0	0	0	0	0	0	0	0
Northern Sub-Saharan Africa	1	1	1	151	130	281	35	30	65
Central & Western SS Afr.	3	2	5	214	184	397	196	169	366
Southern SS Africa	0	0	0	1	1	2	1	1	1
Eastern SS Africa	NA	NA	NA	NA	NA	NA	NA	NA	NA
Egypt	0	0	0	11	7	18	4	3	7
Turkey	5	3	8	67	40	107	16	9	25
Other W. Asia N. Africa	1	1	2	54	47	101	34	30	64
India	0	0	0	7	5	13	5	3	8
Pakistan	NA	NA	NA	NA	NA	NA	NA	NA	NA
Bangladesh	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other S. Asia	0	0	0	1	1	2	0	0	0
Indonesia	10	8	18	310	227	537	356	261	617
Thailand	2	2	4	28	20	48	74	54	128
Malaysia	5	3	8	71	52	124	155	114	269
Philippines	0	0	1	13	10	23	12	9	20
Viet Nam	2	2	4	172	126	298	74	54	128
Myanmar	1	0	1	28	20	48	22	16	38
Other SE Asia	0	0	1	4	3	7	11	8	19
China	17	12	29	397	291	688	516	378	894
South Korea	12	5	17	39	18	57	254	121	374
Other E. Asia	0	0	0	12	9	21	7	5	13
ROW	1	1	1	16	12	28	30	22	52
Other Small Island States	0	0	1	4	3	7	16	12	28

(d) Estimates based on the lower-bound estimate on calcification (low end of 95% interval)

(unit: million USD)

Region	No income rise			Van Vuuren GDP 2100			Gaffin GDP 2100		
	-Δ[Cons. Surplus] (A+B)	-Δ[Prod. Surplus] (C-A)	Total net loss (A+B)	-Δ[Cons. Surplus] (A+B)	-Δ[Prod. Surplus] (C-A)	Total net loss (A+B)	-Δ[Cons. Surplus] (A+B)	-Δ[Prod. Surplus] (C-A)	Total net loss (A+B)
World	**4,946**	**5,195**	**10,140**	**86,195**	**93,841**	**180,036**	**109,650**	**119,024**	**228,674**
USA	294	317	611	878	946	1,824	856	922	1,778
EU 15	396	411	807	999	1,035	2,034	1,010	1,047	2,057
Japan	375	287	662	501	383	884	535	409	944
Australia	31	32	64	73	76	148	62	65	127
Other Dev'd countries	174	181	355	568	589	1,158	1,434	1,486	2,920
East. Europe	4	4	8	43	41	85	61	58	119
Central Asia	NA	NA	NA	NA	NA	NA	NA	NA	NA
Rest Former USSR	22	24	46	424	465	889	408	449	857
Mexico	39	37	75	429	407	836	472	448	920
Brazil	7	6	13	62	59	121	80	76	156
Argentina	46	43	89	343	325	668	558	530	1,088
Colombia	0	0	0	4	4	7	2	2	4
Other Latin Am.	156	148	304	2,784	2,642	5,426	1,765	1,676	3,441
Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA
Northern Sub-Saharan Africa	1	1	2	202	252	455	47	59	106
Central & Western SS Afr.	3	4	8	288	360	649	265	331	597
Southern SS Africa	0	0	0	6	7	12	3	4	6
Eastern SS Africa	NA	NA	NA	NA	NA	NA	NA	NA	NA
Egypt	0	0	1	15	14	29	6	6	12
Turkey	8	7	15	99	94	193	23	22	45
Other W. Asia N. Africa	2	2	4	84	104	188	53	66	120
India	1	1	2	40	44	84	26	28	54
Pakistan	NA	NA	NA	NA	NA	NA	NA	NA	NA
Bangladesh	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other S. Asia	0	0	0	1	1	3	0	0	1
Indonesia	14	16	30	418	459	877	480	528	1,008
Thailand	20	22	41	249	274	523	665	731	1,397
Malaysia	13	14	27	204	224	428	444	488	932
Philippines	2	2	4	77	85	162	67	73	140
Viet Nam	30	33	63	2,075	2,281	4,356	896	985	1,880
Myanmar	1	1	2	37	41	78	30	32	62
Other SE Asia	1	0	0	12	14	26	32	35	67
China	3,180	3,494	6,674	74,184	81,520	155,705	96,468	106,007	202,474
South Korea	110	88	198	369	294	663	2,424	1,937	4,361
Other E. Asia	15	16	31	736	808	1,544	437	481	918
ROW	1	1	2	22	25	47	42	46	87
Other Small Island States	1	1	2	7	8	15	27	29	56

(e) Estimates based on the mean effect size on survival

(unit: million USD)

Region	No income rise			Van Vuuren GDP 2100			Gaffin GDP 2100		
	-Δ[Cons. Surplus] (A+B)	-Δ[Prod. Surplus] (C-A)	Total net loss (A+B)	-Δ[Cons. Surplus] (A+B)	-Δ[Prod. Surplus] (C-A)	Total net loss (A+B)	-Δ[Cons. Surplus] (A+B)	-Δ[Prod. Surplus] (C-A)	Total net loss (A+B)
World	**3,096**	**1,945**	**5,041**	**54,347**	**33,599**	**87,946**	**69,128**	**42,566**	**111,694**
USA	181	144	325	539	430	969	526	419	945
EU 15	243	185	428	612	466	1,079	619	472	1,091
Japan	228	118	346	304	158	462	325	168	493
Australia	19	15	34	45	34	79	38	29	67
Other Dev'd countries	107	81	188	349	265	614	879	670	1,549
East. Europe	3	1	4	27	14	41	38	19	58
Central Asia	NA	NA	NA	NA	NA	NA	NA	NA	NA
Rest Former USSR	14	9	23	267	166	433	258	160	418
Mexico	24	12	36	270	134	404	297	148	445
Brazil	4	2	6	39	19	58	50	25	76
Argentina	29	14	43	216	107	323	351	175	526
Colombia	0	0	0	2	1	4	1	1	2
Other Latin Am.	98	49	147	1,751	873	2,624	1,111	553	1,664
Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA
Northern Sub-Saharan Africa	1	0	1	128	95	223	30	22	52
Central & Western SS Afr.	2	2	4	183	135	318	168	125	293
Southern SS Africa	0	0	0	3	3	6	2	1	3
Eastern SS Africa	NA	NA	NA	NA	NA	NA	NA	NA	NA
Egypt	0	0	0	9	5	14	4	2	6
Turkey	5	2	7	62	31	93	15	7	22
Other W. Asia N. Africa	1	1	2	53	39	92	34	25	59
India	0	0	1	25	16	41	16	10	26
Pakistan	NA	NA	NA	NA	NA	NA	NA	NA	NA
Bangladesh	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other S. Asia	0	0	0	1	1	1	0	0	0
Indonesia	9	6	14	264	164	427	303	188	491
Thailand	12	8	20	157	98	255	420	260	680
Malaysia	8	5	13	129	80	208	280	174	454
Philippines	1	1	2	49	30	79	42	26	68
Viet Nam	19	12	31	1,310	812	2,122	566	351	916
Myanmar	1	0	1	24	15	38	19	12	30
Other SE Asia	1	0	1	8	5	13	20	13	33
China	2,007	1,244	3,252	46,831	29,032	75,863	60,897	37,753	98,650
South Korea	69	26	95	231	87	318	1,518	572	2,090
Other E. Asia	9	6	15	464	288	752	276	171	447
ROW	1	0	1	14	9	23	26	16	43
Other Small Island States	0	0	1	4	3	7	17	10	27

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