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International Journal of Oceanography & Aquaculture

Ocean Acidification and the Economic Impacts on the Molluscs and Crustaceans Markets: A Worldwide Application

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Research Article

Volume 1 Issue 1

Received Date: November 18, 2016

Published Date: February 07, 2017

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Abstract

In the paper, we take an economic perspective in order to assess the impact of ocean acidification (OA) on the aquaculture sector. We define a simple microeconomic model, where society is represented by a representative consumer of aquaculture products, a representative producer of aquaculture products and a policy maker. OA affects production and yields are the key variables that affect consumer, producer and policy maker's objective functions. Under such framework, we simulate changes in the future yields (2010) of mollusks and crustaceans in the top 10 markets worldwide. Results show that OA can both generate gains or losses, according to the biological scenario we embrace for producing predictions. Inaction, adaptation and mitigation policies are finally discussed.

Keywords: Aquaculture markets; Ocean acidification; Microeconomic modeling; Adaptation; Mitigation

Introduction

Aquaculture is the world's fastest-growing food production activity based on animal protein. In fact, over 500 million people depend-directly or indirectly – on aquaculture. Aquatic foods provide essential nutrition for 4 billion people and at least 50% of animal protein and minerals to 400 million people in the poorest countries. Fish products are among the most widely-traded foods, with more than 37% by volume of world production traded internationally [1]. In addition, aquaculture represents an important sector of the blue economy and to the blue GDP. For instance in China, in 2010, aquaculture accounts for almost 1% of total GDP. Finally, aquaculture allows minimizing the pressure on marine resources by offering valid substitutes to fishery products.

Aquaculture activities, however, are exposed to several stressors that can negatively impact the benefits produced by the sector. Ocean acidification is an important driver of change and one of those stressors. As agreed by the international community OA is an irreversible process. It is the marine counterfactual of terrestrial climate change and has both a direct physiological effect on fish (1) and an indirect impact on economic activities, including aquaculture.

However, if we know that OA is an irreversible process, we do not exactly how and how much it will affect aquaculture yields. There is a large gap in scientific and economic research.

In the paper, we attempt to address the gap. We take an economic perspective in order to assess the impacts of OA on the aquaculture sector (in particular molluscs and crustaceans segments). In our framework, OA affects consumption and production choices, therefore affecting markets, and social welfare. In this perspective, the main questions addressed in the study are:

(1) What are the future impacts of OA on aquaculture production and on social welfare?

(2) What policies can be defined (and what are their impacts in terms of cost-benefits analysis) for adapting/mitigating the future impacts of OA on aquaculture production and on social welfare when selected (adaptation and mitigation)?.

The motivation of question (1) is due to the fact that the impacts of OA are very uncertain and often studies present contradictory results: the "state-of-the art" research shows that OA can have positive or negative impacts on aquaculture yields. Therefore, before proposing a targeted policy, we must compute the possible impacts on the markets under different cases. In order to do so, we use the framework by Armstrong (see below Section 5) and FAO data in order to compute the impacts of OA in selected aquaculture segments (mollusks and crustaceans) in the top 10 producer countries (that account for almost 90% of the aquaculture world production).

The paper is organized as follows. Section 2 describes the impacts of OA on the environment and selected economic sectors. Section 3 describes and surveys the economic literature related to the impacts of OA on aquaculture. Section 4 presents a simple economic model that provides a framework for understanding the impacts of OA on the aquaculture markets. Section 5 presents an application of the model to the ten top worldwide producers of mollusks and crustaceans. It also presents predictions of the yields in 2010, given the economic model and the technical background provided by experts. Section 6 discusses different policies (inaction, adaptation, mitigation) to be applied to the sector impacted by OA. Section 7 concludes.

Ocean Acidification: Environmental and Economic Impacts

Oceans are an important reservoir of carbon and, from the economic perspective, source and inputs of productive activities and welfare, as explained in the previous paragraphs. The average acidity of the global oceans has increased, however, by 30% (decreasing pH from 8.2 to 8.1) since the beginning of the Industrial Revolution, and the increase in acidity is expected to increase three-fold (yielding a decrease in pH to 7.8) by the end of this century if CO_2 emissions continue at current rates.

Ocean Acidification: Environmental Impacts

The ocean reservoir of carbon provides an important net sink for carbon through exchanges of CO_2 with the atmosphere. Hilmi et al. report that over the past 200 years, atmospheric CO_2 has increased from 280 ppm to a global average of nearly 390 ppm as a result of fossil fuel emissions, cement manufacture and land use changes. Carbon uptake by the ocean has slowed the atmospheric increase and its associated consequences for the Earth's climate: without such uptake, it is estimated that atmospheric CO_2 would now be around 400 ppm (source www.co2.earth). The increase in the rate of addition of CO_2 to seawater by air-sea gas exchange due to increasing anthropogenic CO_2 in the atmosphere is leading to an increase in hydrogen ion (H+) concentrations, and hence a fall in pH. Dissolved CO_2, carbonic acid, and bicarbonate are also increasing; however, the concentration of carbonate ions is decreasing as a result of a reaction between CO_2 and carbonate, further increasing bicarbonate levels. Uptake of this additional CO_2 has already increased the average acidity of the global ocean by 30% (decreasing pH from 8.2 to 8.1) since the beginning of the Industrial Revolution, and the increase in acidity is expected to increase three-fold (yielding a decrease in pH to 7.8) by the end of this century if CO_2 emissions continue at current rates. Therefore, absorption of CO_2 by the oceans at a rate of 25 million tons of CO_2 per day contributes to the mitigation of global warming, but at a cost to ocean carbonate chemistry.

Ocean acidification (OA) is the term used to describe these changes in ocean chemistry. It is anticipated that OA could have dramatic consequences this century, potentially including extinction of keystone marine species [2].

Organisms producing a carbonate shell or skeleton have been the primary research focus to date, as calcification partly depends on carbonate ion concentration. Evidence is increasing that organisms respond to OA to variable degrees [3-5] and that sensitivities differ between species, with some species showing negative responses while others show no or positive responses [6]. Direct consequences of decreasing seawater pH, such as changes in growth rates, are mediated through changes in acid-base status or shifts in energy budget. These effects also depend on species-specific capacities to compensate. Additional physiological disturbances have been reported, including behavioral changes, reductions in fertilization and reproductive success through development effects to eggs, larvae, and juveniles [7]. Impacts from OA can be modulated and exacerbated when combined with other environmental parameters such as food availability, temperature increases or hypoxia [8,9]. Projected future changes at the ecosystem level could include relative shifts in fitness and competitiveness, changes in species interactions and biogeography, and ecosystem restructuring due to synergistic effects with temperature and changes in species composition and biodiversity. Marine organisms also may be indirectly at risk due to OA's effects on key components of food webs, for example, on phytoplankton quality or specific zooplankton such as pteropods that are essential in the diets of salmon and whales [10]. There has been a growing awareness that many of the goods and services provided by the ocean may be at risk from increasing OA, and for this reason there could be far reaching socio-economic consequences [11,12].

Ocean Acidification: Economic Impacts

Despite the potentially several impacts of ocean acidification on marine ecosystem services, there has been relatively little research on the economic costs involved. There is little knowledge yet on how, where and how much OA will negatively impact economic activities and welfare. The work of Brander et al. provides an excellent survey of studies that address the issue of economic impacts of ocean acidification. In particular, the authors highlight the following issues:

A. Most studies have focused on impacts to commercial fisheries and aquaculture that appear to be the marine economic sectors "more directly" impacted by OA. Ocean acidification, a consequence of rising anthropogenic CO_2 emissions, is poised to change marine ecosystems profoundly by increasing dissolved CO_2 and decreasing ocean pH, carbonate ion concentration, and calcium carbonate mineral saturation state worldwide. These conditions hinder growth of calcium carbonate shells and skeletons by many marine plants and animals. The first direct impact on humans may be through declining harvests and fishery revenues from shellfish, their predators, and coral reef habitats. This could lead to a sharp decrease in catches and export earnings. Local economies and employment, in particular in developing countries, would be greatly impacted, some of them threatening to collapse. The risk of food insecurity also might increase the severity of social impact. Livelihoods are being impacted through loss of habitat (such as coral reefs) caused by acidification. Coral reef degradation, due to OA, can also impact coastal tourism.

B. The geographic scale of analysis of studies examining the economic impacts of ocean acidification is mostly very large (mostly global). Most probably ocean acidification will have highly localized ecological and social impacts. The impact on economic welfare can be expected to vary across locations depending on the localized degree of acidification, the sensitivity of ecosystems to acidification and the extent to which they are already under pressure, the dependence of the population on impacted ecosystem services (e.g. fisheries, coastal tourism), and the capacity to adapt to losses in the provision of those services.

C. The methodologies adopted in the studies are different and are based on a broad range of approaches, spanning from gross revenues from fishing, to damage costs from increased climate change; from estimate changes in both consumer and producer surplus to compensating variation measure of consumer welfare, to using a meta-analytic value function that is derived from a mix of underlying welfare estimates (including both consumer and producer surplus). The heterogeneity of adopted methodologies, used to estimate welfare measures, rules out direct comparisons.

D. Only a few studies provide monetary estimates of the costs of ocean acidification. As more deepened in paragraph 5.1, the authors highlight that three of these are for impacts on mollusc fisheries (two for the US and one global estimate); one covers impacts on fisheries and carbon storage; and one is for impacts on coral reef services levels. The impacts to coral reef services dominate. The global annual loss in value of coral reef services in 2100 is estimated to be an order of magnitude higher than that of mollusc fisheries.

The estimated increased damage cost of climate change associated with reduced carbon storage due to ocean acidification suggests that this is also a potentially important impact category. The cost of this feedback effect to climate change has currently only been roughly estimated for the Norwegian Exclusive Economic Zone. The current information on the damage costs of ocean acidification only provides a partial assessment of total impacts given that other impact categories, particularly fin fisheries, are yet to be widely assessed.

Impacts of Ocean Acidification on Aquaculture

Aquaculture can be impacted by ocean acidification due to physiological impacts at the single organisms' level; followed by effects on ecosystem level, changes in habitats, and in the food web [13]. These impacts can be negative as well as positive [14]. In general, the early life stages of fish such as eggs, larvae and juveniles are considered to be more vulnerable to changes in environmental conditions [15]. Whereas adult marine fish appear to be highly tolerant to elevated CO_2-levels [16,17]. As the early life-stages of fish in aquaculture are raised in land-based tank-systems, they are not exposed to ocean acidification. In freshwater experiments salmon parr (i.e. young fishes, ca. 10-13g) have showed reasonable tolerance to elevated CO_2 levels [18]. Thus, it can be expected that salmon when put in ocean pens may be old enough to withstand the expected elevated CO_2 levels. Cod fertility is likely to be robust in the face of near-future ocean acidification [19], but further pH reductions i.e. below the expected values for 2100 may lead to weight reductions in young cod [20]. With regards to the direct physiological effects of OA upon marine organisms, these can roughly be grouped in three main types: 1) changes in internal acid-base balance, 2) impacts upon reproduction and early development, and 3) effects on calcification [21]. Regarding internal acid-base balance, active animals such as most fish species, squid and some crabs, are expected to be less sensitive to changes in acid-base balance, as CO_2 builds up naturally in their bodies during active movement [22]. Furthermore, early life stages are often more vulnerable than fully grown individuals, and may therefore be expected to be more severely impacted by ocean acidification. Calcifying organisms, such as molluscs, are expected to be amongst the first organisms to be affected by ocean acidification and yet it may not be the actual calcification that is threatened by ocean acidification, but rather other activities [23-25].

Literature Survey

There are very few economic studies that measure an impact of OA in fishery and aquaculture. Table 1 summarizes the main findings.

Study	Impacts	Geographic Scope	Period of Analysis	Welfare Measure[1]	Annual Value (US$; billions)[2]
Armstrong et al. (2012)	Fisheries/ aquaculture	Norway	2010 – 2110	Revenue	0.01
Cooley and Doney (2009)	Fishery (Mollusks)	United States	2007 – 2060	Revenue	0.07
Moore (2011)	Aquaculture (Mollusks)	United States	2010 – 2100	CV	0.31
Narita et al. (2012)	Aquaculture (Mollusks)	Global	2000 – 2100	CS, PS	139

Table1: Summary of studies that examine the economic impacts of ocean acidification on aquaculture activities.
Source: Selection from Brander et al. 1 CV: compensating variation; CS: consumer surplus; PS: producer surplus.

Armstrong et al. describe a preliminary analysis of the potential impacts of ocean acidification in Norwegian waters. The study identifies the marine ecosystem services that are likely to be affected by ocean acidification, the economic methods to assess the impacts, and the present knowledge gaps. The study also produces a preliminary analysis of the scale of possible damage costs from ocean acidification with a focus on provisioning and regulating services. The results of this analysis show that ocean acidification may have positive as well as negative effects fisheries and aquaculture [26].

Cooley and Doney estimate the impact of ocean acidification on gross revenues for US mollusk fisheries up to 2060 [27]. They combine experiment level information on the impact of ocean acidification on growth rates of mollusks with data on US fisheries harvests and prices. Baseline future revenues are projected to 2060 assuming no changes in ecological and economic conditions prevailing in 2007 (i.e., catch, prices and revenues remain constant). Under an ocean acidification scenario, the time profile of increasing impacts on mollusk growth is assumed to be linear and proportionately related to revenue for the period 2007-

2060. The estimated present value of losses in revenue are shown to be sensitive to CO_2 emission trajectories, impacts on mollusk growth and the discount rated used in calculating present values. Under the IPCC A1F1 scenario, the present value of lost revenue is estimated to be US$ 2,557 million (25% reduction in mollusk growth at 740 ppm CO_2; 2% discount rate).

Moore (2011) develops an integrated biogeochemical-economic model to estimate the potential impacts of ocean acidification on the US market for oysters, scallops, clams, and mussels for the period 2010-2100 [28]. The welfare measure that is estimated is the compensating variation of US households. Compensating variation reflects the change in consumer welfare following a change in prices and is defined as the amount of additional income that a household would need in order to obtain their original level of utility prior to a price increase. The estimated impact therefore represents the loss in consumer welfare due to increased mollusk prices caused by ocean acidification. The present value of aggregated reduced consumer welfare is estimated to be US$ 735 million for the period 2010-2100 using a discount rate of 5%. The author identifies the most tenuous link in the integrated model to be the relationship between changes in mollusk growth rates and prices.

Narita et al. estimate the value of global and regional loss of mollusk production due to ocean acidification over the period 2000-2100. A partial-equilibrium analysis is used to quantify both producer and consumer surplus and accounts for two determinants of welfare change, namely reduced production/consumption and increased prices [29]. The results show that the annual global costs in 2100 could be over 100 billion US$ under a business-as-usual emission trend and assuming that demand for mollusks increases with income, the trend for which is based on the IPCC projections. The major determinants of this cost estimate are the impacts on Chinese production, which is projected to dominate global production, and the expected increase in demand for mollusks in developing countries, including China, in accordance with future income rise. The analysis also indicates that in key regions such as China and the USA, the economic losses are roughly evenly divided between producers and consumers, with slightly greater relative consumer losses for China as a result of relatively inelastic demand of mollusks in that country.

An Economic Model of the Impacts of OA on Aquaculture

We can model the impact of OA in aquaculture in a strictly neoclassical microeconomics framework (2) in order to frame economic agents' behavior and be able to predict and measure (in monetary terms) the impacts of OA in aquaculture markets. Our model considers a representative society, where there are consumers, producers and a policy maker. The economic agents consume, produce and exchange aquaculture products. Therefore, the effects of ocean acidification really impact their objective functions, in the way explained below. The model aims at isolating the key variable(s) that can be used in the prediction exercise that follows in the next paragraph.

In this perspective, the representative consumer of aquaculture products (3) has an objective function as characterized by Equation 1, the utility function (4). The consumers' utility depends on the consumed quantity Q of aquaculture products that in turn depends on the product price (p) and the ocean environmental quality (K) that can be affected by OA.

$$(1)\, U_Y = Q(p_y; K_y)$$

We assume that (1) $\frac{\partial U_y}{\partial Q_y} . \frac{\partial Q_y}{\partial p_y} < 0$. This means that a

marginal increase in price spurs the consumer to consume less aquaculture products. This, in turn, negatively affects consumer's utility. Price, however, is not a variable directly affected by OA.

We also assume that (2) $\frac{\partial U_y}{\partial Q_y} . \frac{\partial Q_y}{\partial K_y} \neq 0$. In equation 2,

this means that marginal changes in environmental quality, due to OA variations, affect the quantity consumed and this, in turn, affects consumers' utility, but we are not able to make a quantitative prediction. In fact, we know that environmental quality determined by OA is an important variable in the model, however we do not know in what "direction" (if negative or positive) OA affects the consumed quantity.

The representative aquaculture producer's objective function is described by Equation 2.

$$(2)\ \pi_y = Q_y(p_y; c_y K_t)$$

Profits π_y depend on the produced quantity Q, that in turn depends on the sale price (p) of the yth aquaculture product, the production costs (c) and again and the ocean environmental quality (K) that can be affected by OA. Profits are maximized when (1) $\frac{\partial \pi_y}{\partial Q_y} \cdot \frac{\partial Q_y}{\partial p_y} = \frac{\partial \pi_y}{\partial Q_y} \frac{\partial Q_y}{\partial c_y}$. This means that marginal production costs equal marginal revenues. In particular, profits are also affected by (2) $\frac{\partial \pi_y}{\partial Q_y} \cdot \frac{\partial Q_y}{\partial K_y} \neq 0$. This means that marginal increases in the level of K (e.g. determined by OA) affect the produced quantity and this, in turn, affects producer's profits. Again, OA affects human choices (consumption and production, in this latter case), and therefore markets (5).

Finally, the policy maker's objective function is a simple utilitarian function that represents social benefits (derived from consuming and producing aquaculture products) and is generated by the sum of producer and consumer surplus (e.g. producers' profits and consumers' utility). In this perspective, OA indirectly impacts both the utility of consumers and the profits of producers, by affecting K, and Q. Therefore the effects of OA have impacts on the produced and consumed total quantity and, therefore, it has an effect on total benefits, captured by the social welfare function. In order to predict in 100 years' time (and quantify in monetary terms) the OA effects on social welfare, we adopt a simple Benthamite welfare function, as described in Equation (3). In the function, social welfare depends on aquaculture yields Q, We know from Equation (1) and (2) that Q is affected by OA. Therefore the variations of yields in the next 100 can positively or negatively affect social welfare (in the representative society that we have modeled). Understanding and predicting how and how much also helps in designing policies.

3) $$W_{y.t} = \int_0^{100} W(Q(t)dt$$

We can sum up that in our simple framework; the key variable affected by OA is the quantity of aquaculture products. This, in turn, affects consumers' utility, producers' profits and social welfare. We can, then, proceed with the following, research/policy questions:

1. What are (and how much are worth) the future impacts of OA (K) on aquaculture production (Q) and on social welfare (W)?
2. What are the impacts in the future of OA (K) on aquaculture production (Q) and on social welfare (W) with selected (adaptation/mitigation) policy measures?

Section 4 provides a numerical simulation that addresses question 1. Question 2 is discussed in section 5.

A Numerical Simulation with an Application to Molluscs and Crustaceans

We present an application of our simple model to the top 10 world aquaculture producers of mollusks and crustaceans. We have performed a numerical simulation, given limited available, following the steps we are explaining in the paragraph.

Table 2 shows the top 10 world aquaculture producers in 2010. We assume that those countries are presumably the most affected by OA negative impacts.

Country	Tonnes	% on Total Production	Value in 2010 Billion Dollars	% of National Gdp
China	36 734 215	61.35	76.68	0.95
India	4 648 851	7.76	9.7	0.73
Vietnam	2 671 800	4.46	5.57	3.57
Indonesia	2 304 828	3.85	4.81	0.54
Bangladesh	1 308 515	2.19	2.73	2.35
Thailand	1 286 122	2.15	2.68	0.73
Myanmar	850 697	1.42	1.77	N/A
Philippines	744 695	1.24	1.55	0.62
Norway	1 008 010	1.68	2.1	0.42
Egypt	919 585	1.54	1.92	0.7
Other	7 395 281	12.35	15.43	-
Total	59 872 600	100	125	-

Table 2: Top ten regional and world aquaculture producers in 2010.
Source: FAO and World Bank

It is interesting to highlight that Asia accounted for 89 percent of world aquaculture production by volume in 2010, up from 87.7 percent in 2000. Asian aquaculture is dominated by finfishes 64.6 percent), followed by molluscs (24.2 percent), crustaceans (9.7 percent) and miscellaneous species (1.5 percent). The contribution of China to world aquaculture production volume in 2010 declined to 61.4 percent from its highest level of about 66 percent in the period 1996–2000. Other major producers in Asia (India, Viet Nam, Indonesia, Bangladesh, Thailand, Myanmar, the Philippines and Japan) are among the world's top producers. It is worth highlighting that aquaculture accounts for about 1% of total China GDP. Africa has increased its contribution to global production from 1.2 percent to 2.2 percent in the past ten years, albeit from a very low base, largely reflecting the strong growth in brackish-water culture in Egypt (6).

OA can have positive or negative impacts on aquaculture yields/quantity. Therefore, before proposing a targeted policy, we must compute the possible impacts on such key variable (Q in our model). Since most studies assume a 100 years' time horizon for prediction we also assume that time horizon. The methodology is very simple. Table 3 provides information on production value and volume of molluscs and crustaceans in the top 10 world aquaculture leaders in 2010. We have adopted a 2% discount rate for the period. Values are computed and presented in Table 3. This is an exercise instrumental to predict, as explained in what follows.

Country	Tonnes of Mollusks	Tons of Crustaceans	Value in 2010 billion dollars mollusks	Value in 2010 billion dollars mollusks
China	9183553.8	6.13	19.25	7.66
India	1162212.8	0.77	2.425	0.97
Vietnam	667950	0.46	1.4	0.55
Indonesia	576207	0.38	1.22	0.48
Bangladesh	327128.75	0.21	0.7	0.27
Thailand	321530.5	0.21	0.67	0.26
Myanmar	212674.25	0.14	0.45	0.17
Philippines	186173.75	0.12	0.38	0.15
Norway	252002.5	0.16	0.52	0.21
Egypt	229896.25	0.15	0.48	0.19

Table 3: Value and volume of molluscs/crustaceans in the top 10 world producers in 2010.
Source: FAO (2012).

Without OA and assuming a 2110 ceteris paribus scenario (i.e. nothing changes in term of consumers, producers and policy maker's objective functions determinants, like prices or production costs), we can predict that the future value in 2110 of the selected segments of the aquaculture sector are ones reported on column 3 and 5 of Table 4.

Country	Value in 2010 billion dollars mollusks	Value in 2110 billion dollars mollusks	Value in 2010 billion dollars crustaceans	Value in 2110 billion dollars crustaceans
China	19.25	139.46	7.66	55.49
India	2.42	18.11	0.97	7.03
Vietnam	1.4	10.14	0.55	3.98
Indonesia	1.22	8.84	0.48	3.48
Bangladesh	0.7	5.07	0.27	1.96
Thailand	0.68	4.93	0.27	1.96
Myanmar	0.45	3.26	0.18	1.3
Philippines	0.39	2.83	0.15	1.09
Norway	0.52	3.84	0.21	1.52
Egypt	0.48	3.55	0.19	1.38

Table 4: Present and future values of the yields of top 10 molluscs and crustaceans world producers.
Source: own elaboration from FAO.

Starting from this quantitative information, we adopt the results of the study by Armstrong et al. [25] in order to make an application of the model and predict impacts of OA on the selected mollusk and crustaceans yields (Q). In order to start, we adopt a strong assumption (that can be changed afterwards): market's fundamentals (consumers' preferences and budgets that affect demand, production technologies that affect supply, prices) do not change across time. Coherent with our microeconomic framework, what changes are total only yields (Q. because of OA effect) that affects producers 'profits, consumers 'utility and policy-makers' welfare functions. The OA impacts are provided by the study of Armstrong et al. In particular, in the authors' framework two key scenarios are highlighted:

1. The best case scenario: where OA positively affects mollusks and crustaceans yields of 2.7% and 5.58% respectively.
2. The worst case scenario: where OA negatively affects mollusks and crustaceans yields of 59.44% and 26.55% respectively With such scenarios, we use the figures computed in Table 4 and can predict how the quantity and value valued of future yields of selected aquaculture products (Q) will vary in 2110. Table 5 and 6 report simulation results.

Country	Best Scenario	Total Gains	Worse Scenario	Total Loss
China	143.22	3.76	56.57	82.89
India	18.6	0.49	7.35	10.76
Indonesia	10.41	0.27	4.12	6.02
Vietnam	9.07	0.23	3.59	5.25
Bangladesh	5.21	0.14	2.06	3.01
Thailand	5.06	0.13	2	2.93
Myanmar	3.34	0.08	1.32	1.94
Philippines	2.9	0.07	1.15	1.68
Norway	3..94	0.1	1.56	2.28
Egypt	3.64	0.09	1.44	2.11

Table 5: OA economic in the in the top 10 world molluscs producers in 2110.
Source: Our elaboration.

Country	Best Scenario	Total Gains	Worse Scenario	Total Loss
China	58.58	3.09	40.75	14.73
India	7.42	0.39	5.163	1.86
Indonesia	4.2	0.22	2.92	1.05
Vietnam	3.67	0.19	2.55	0.92
Bangladesh	2.07	0.11	1.44	0.53
Thailand	2.06	0.1	1.43	0.52
Myanmar	1.37	0.07	0.95	0.34
Philippines	1.15	0.06	0.8	0.28
Norway	1.6	0.08	1.11	0.4
Egypt	1.45	0.07	1.01	0.36

Table 6: OA economic in the in the top 10 world crustaceans producers in 2110

Finally, Figure 1 and 2 present a synthesis between the model in 2010 and 2110.

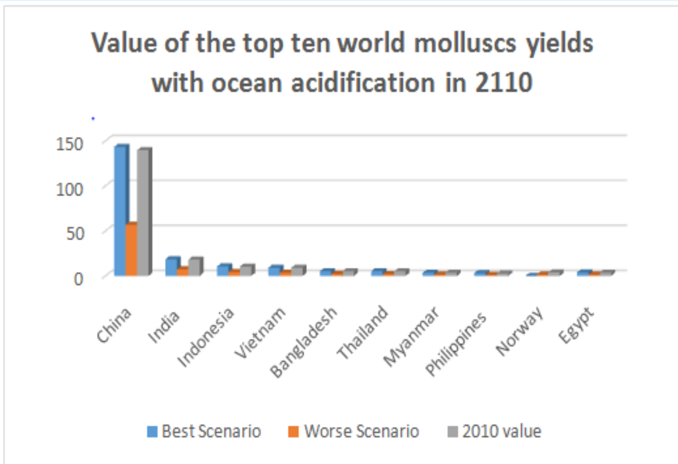

Figure 1: Comparisons between 2010 and 2011 values of the molluscs yields.

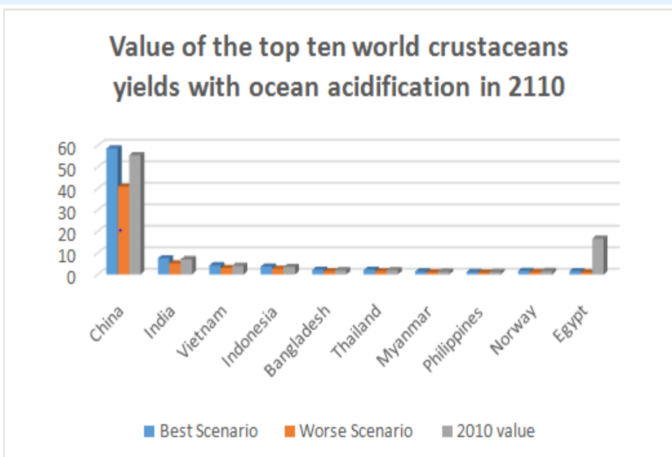

Figure 2: Comparisons between 2010 and 2011 values of the molluscs yields.

Tables 5-6 and Figures 1-2 show that we can simulate contradictory results. Therefore, without a policy intervention, or adopting a voluntarily "inaction policy", the effects can span from gains (and related positive impacts on social welfare) to losses (and subsequent negative impacts on welfare) due to OA impacts (the increase/decrease yields, ceteris paribus) in selected aquaculture segments.

Inaction, Adaptation and Mitigation: Comparing Costs and Benefits of OA on Aquaculture in Order to Design Policies

If the policy maker is very optimistic (or an OA adaptation/mitigation policy presents very high opportunity costs) she can "believe" in the "best case scenario" and opt for inaction. But, what to do in case the policy maker believes in the worse scenario? As highlighted by Hilmi et al, the level of knowledge is still too low and fragmented and scarce in order to define and submit to CBA realistic policies. However, some hints for discussion can be highlighted [30].

Our results show that total losses due to OA in the crustaceans and mollusk segment of the aquaculture markets could be 20.99 and 118.87 billion dollar respectively in 2110. The results of Narita et al, in addition, show that the annual global costs in 2100 could be over 100 billion US$ under a business-as-usual emission trend and assuming that demand for mollusks increases with income. These figures represent a "baseline cost" that the policy maker must incur if she wants to keep the current production level (Q), in our example, or under the assumption that the demand for mollusks increases with income (7). In our case, the target "Keep the status quo" (or the same level of welfare) could cost society around 118 billion dollars in 2110.
If the policy maker does not want to be inactive, we have to highlight that adaptation (8) and mitigation (9) policies are very difficult to design.

Adaptive capacity, in fact, is determined by the availability of substitute production and consumption options and by the (opportunity) costs of the substitution. For ocean acidification, there are a number of potential adaptation options. For example, as discussed by Narita et al, aquaculture may be able to insulate itself from or mitigate the effects of acidification by relocating farms to closed waters or in creating and at adopting varieties resistant to acidity. Governments may subsidize R&D programs that aim at development of production technologies that adapt to OA/mitigate OA effects on yields. At the same time, in such a long term perspective, the analyst might consider an evolution in consumers' tastes and production technologies. Our predictions and simulations are based on assumptions based on today's behavior.

More in general, as noted by Brander et al. adaptation strategies might be designed once the casual links between OA and impacts on nature and humans are clearly explained and identified. Adaptation, in fact, generally incurs costs, and actions are warranted only if the benefits outweigh the costs. At present, little economic analysis has been done with regard to the costs of adaptation to ocean acidification, and more research is needed on this subject. One of the objectives of this challenge paper is stimulating debate and research. There are still considerable gaps in knowledge. These gaps refer to (1) understanding the relation between changes in the marine environment and socio-economic impacts, (2) the ecosystem services that have been assessed, (3) the distribution of impacts and (4) the vulnerability of different populations. These individual gaps are discussed in more detail in this section [31].

Mitigation policies can be threefold. A first group of measures refers to "strategic Location/aquaculture zoning". For example, as discussed by Narita et al. aquaculture may be able to insulate itself from or mitigate the effects of acidification by relocating farms to closed waters or in creating and at adopting varieties resistant to acidity [29].

A second group of measures may focus on diversifying livelihood systems. For instance, for livelihoods based on culturing pearls, adaptations to reduce the consequences of ocean acidification include growing oysters in deeper water, producing selectively bred spat in hatcheries and identifying sites where concentrations are adequate to produce high-quality pearls.

More in general, mitigation policies should aim at aquaculture diversification. In many countries and regions, there is a clear tendency to diversify farmed species and technologies. The aquaculture of extractive species (using nutrients and carbon directly from the environment) such as bivalves and macro-algae may deserve further attention for their positive ecosystem characteristics and potential food security benefits. Integrating aquaculture with other practices, including agro-aquaculture, multi-trophic aquaculture and culture-based fisheries, also offers the possibility of recycling nutrients and using energy and water much more efficiently. These could include fisheries and assist coastal communities in general. Short cycle aquaculture may also be valuable, using new species or strains and new technologies or management practices to fit into seasonal opportunities. Gain may also come from better stock selection, larger scale production methods, aquaculture in open seas and larger inland water bodies, and a culture of a wider range of species [32].

Finally, an important step towards understanding and attempting to adapt and mitigate OA is the interaction between biologists and economists that might enhance the credibility of environmental research in the eyes of the public and decision-makers and will shed new light on the consequences of OA. Such collaborative interaction appears necessary to undertake a holistic, multidisciplinary quantitative assessment that provides targeted information and data. (10) With this information, integrated assessment.

Conclusion

In this paper, we have attempted to address the issue of understanding and measuring the impacts of OA in aquaculture markets. We have constructed a simple microeconomics framework and shown an application. Our results have to be interpreted and OA is an irreversible process. Several factors affect the predictability of OA effects on aquaculture markets and include:

- Ability of consumers to respond to changes in demand and supply
- Changes in fishing ranges
- Changes in micronutrients
- Increased risks to aquaculture investments (e.g. decreased productivity and growth rates, increased mortality)

There is not a clear measure in the scientific literature that quantifies the causal link between ocean acidification/Ph decrease and effects on animals/aquaculture yields (e.g. ph changes and effects on the calcium of the shells of crustaceans). There are few studies in the economic literature that look at the economic impacts on aquaculture. Some studies suggest that there may be a substantial reduction in potential aquaculture yields in more acidic waters. Others suggest that OA may even increase yields. This would impact upon quantity, quality and predictability of future production. It is therefore very unlikely to formulate quantitative targets and policies, given the current advancements in research and knowledge. One cannot say yet that: "decrease the marine ph of %" will generate an increase /decrease in yields of x%", since the causal links are not well understood yet. Therefore, effective, targeted policies can be designed (and quantitatively predicted) only when we know more and once the casual links between OA and impacts on nature and humans are clearly explained and identified.

Acknowledgement

Laura Onofri would like to thank the participants to the GFCM-CAQ Cattolica Expert meeting on sustainable shellfish aquaculture in the Mediterranean and the Black Sea (23-25 November 2015), in particular Fabio Massa from FAO.

Descriptions

1. For instance, direct physiological effects (Le Quesne and Pinnengar 2011) are: alteration, reduction/inhibition of growth of calcified structures (adult and larvae); acid-base balance; Otolith development; Basal metabolic costs; Aerobic scope; O2 consumption; thermal tolerance; gamete maturation and activation; fertilization success; egg hatching; embryonic development; olfactory behavioural responses.

2. Our model is a microeconomic model. This means, in economic theory, that we use the instruments, provided by neoclassical microeconomic theory and mathematics, in an independent, original way, in order the tackle the problem at issue and to understand and explain human (consumers, producers and policy-makers) behaviour. This also allows prediction.

3. World production of marine fishes is more evenly distributed across the cultured species. However, almost half a million tonnes, or one-quarter of global production, are reported without identifying the species, particularly by a few top producers from Asia. There is evidence that production of European sea bass and gilthead sea bream has been significantly under-reported in some areas in the Mediterranean. World aquaculture production of crustaceans in 2010 consisted of freshwater species (29.4 percent) and marine species (70.6 percent). The production of marine species is dominated by white leg shrimp (*Penaeus vannamei*), including substantial production in freshwater. In sharp contrast, the giant tiger prawn has lost importance in the last decade. Major freshwater species include red swamp crayfish, Chinese mitten crab, oriental shrimp and giant river prawn. Regarding molluscs, aquaculture production of clams and cockles has increased much faster than that of other species groups. In 1990, clam and cockle production was half that of oysters, but by 2008 it exceeded oysters and became the most-produced species group of molluscs. Among other aquatic animals, production of sea cucumbers and soft-shell turtles has increased rapidly.

4. In microeconomics theory, utility is the satisfaction derived from the consumption of goods and services and is described by a utility function.

5. Markets are institutions where consumers and producers meet and exchange goods and services.

6. In North America, aquaculture has ceased expanding in recent years, but in South America it has shown strong and continuous growth, particularly in Brazil and Peru. In terms of volume, aquaculture in North and South America is dominated by finfishes (57.9 percent), crustaceans (21.7 percent) and molluscs (20.4 percent). Bivalve production fluctuated between 14 and 21 percent of total aquaculture production in the 1990s and 2000s, after dropping rapidly in the 1980s from 48.5 percent. In Europe, the share of production from brackish and marine waters increased from 55.6 percent in 1990 to 81.5 percent in 2010, driven by marine cage culture of Atlantic salmon and other species. Several important producers in Europe have recently ceased expanding or have even contracted, particularly in the marine bivalve sector. In 2010, fin fishes accounted for three-quarters of all European aquaculture production, and molluscs for one-quarter. The share of bivalves in total production decreased continuously from 61 percent in 1980 to 26.2 percent in 2010. Oceania is of relatively marginal importance in global aquaculture production. Production from this region consists mainly of marine molluscs (63.5 percent) and fin fishes (31.9 percent), while crustaceans (3.7 percent, mostly marine shrimps) and other species (0.9 percent) constitute less than 5 percent of its total production. Marine bivalves accounted for about 95 percent of the total produced in the first half of 1980s but, reflecting the development of the finfish culture

7. In China, molluscs are usually adopted in traditional cooking. They are not luxury goods, but normal goods. Therefore, an increase in income does not necessarily implies a consumption of more molluscs.

8. OA adaptation' refers largely to questions of evolution, asking whether marine species can evolve swiftly enough to avoid an impending extinction event. Some studies show potential adaptation through storing captured carbon away from seawater; however, these strategies are only cost and energy effective at the very small-scale. The vastness, complexity, and chronic threat of acidification of the planet's oceans render engineering and adaptation a dangerous, cost-prohibitive exercise.

9. Mitigation policies might be designed once the casual links between OA and impacts on nature and humans are clearly explained and identified. Mitigation, in fact, generally incurs costs, and actions are warranted only if the benefits outweigh the costs. At present, little economic analysis has been done with regard to the costs of mitigation ocean acidification, and more research is needed on this subject. Mitigating the effects of AO (what is AO) implies exploiting adaptive capacity that is determined by the availability of substitute production and consumption options and by the (opportunity) costs

of the substitution. For ocean acidification, there are a number of potential options.

10. Information and data need to be carefully collected and mostly refer to: models can be developed that will demonstrate the social welfare impacts of different CO_2 emissions policies on specific regions of the world. An improved, multidisciplinary-based knowledge will allow designing more targeted policies that correctly address issues of differentiated vulnerability in differentiated geographic areas, for different types of economic activities and human capital conditions and livelihoods.

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