Received: 12 February 2020 | Revised: 6 May 2021 | Accepted: 23 May 2021

DOI: 10.1111/nrm.12317

Natural Resource Modeling WILEY

Taxing interacting externalities of ocean acidification, global warming, and eutrophication

Martin C. Hänsel[1] | **Jeroen C. J. M. van den Bergh**[2,3,4]

[1]Transformation Pathsways, Potsdam Institute for Climate Impact Research (PIK), P.O. Box 60 12 03, Potsdam, 14412, Germany

[2]ICREA, Barcelona, Spain

[3]Institute of Environmental Science and Technology, Autonomous University of Barcelona, Barcelona, Spain

[4]School of Business and Economics & Institute for Environmental Studies, VU University Amsterdam, Amsterdam, The Netherlands

Correspondence

Martin C. Hänsel, Potsdam Institute for Climate Impact Research, Telegrafenberg, Germany.
Email: haensel@pik-potsdam.de

Abstract

We model a stylized economy dependent on agriculture and fisheries to study optimal environmental policy in the face of interacting external effects of ocean acidification, global warming, and eutrophication. This allows us to capture some of the latest insights from research on ocean acidification. Using a static two-sector general equilibrium model we derive optimal rules for national taxes on CO_2 emissions and agricultural run-off and show how they depend on both isolated and interacting damage effects. In addition, we derive a second-best rule for a tax on agricultural run-off of fertilizers for the realistic case that effective internalization of CO_2 externalities is lacking. The results contribute to a better understanding of the social costs of ocean acidification in coastal economies when there is interaction with other environmental stressors.

Recommendations for Resource Managers:

- Marginal environmental damages from CO_2 emissions should be internalized by a tax on CO_2 emissions that is high enough to not only reflect marginal damages from temperature increases, but also marginal damages from ocean acidification and the interaction of both with regional sources of acidification like nutrient run-off from agriculture.

- In the absence of serious national policies that fully internalize externalities, a sufficiently high tax on regional nutrient run-off of fertilizers used in agricultural production can limit not only marginal environmental damages from nutrient run-off but also account for unregulated carbon emissions.
- Putting such regional policies in place that consider multiple important drivers of environmental change will be of particular importance for developing coastal economies that are likely to suffer the most from ocean acidification.

KEYWORDS

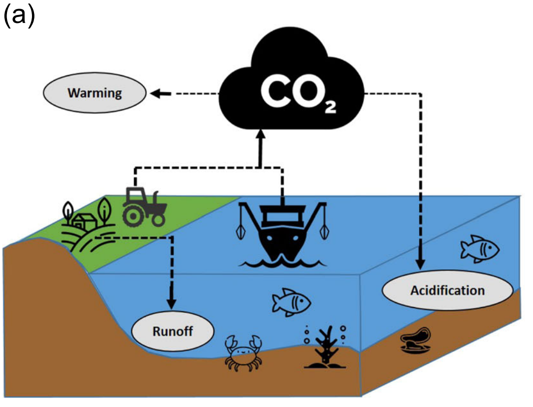
climate policy, eutrophication, externalities, general equilibrium, global warming, ocean acidification

1 | INTRODUCTION

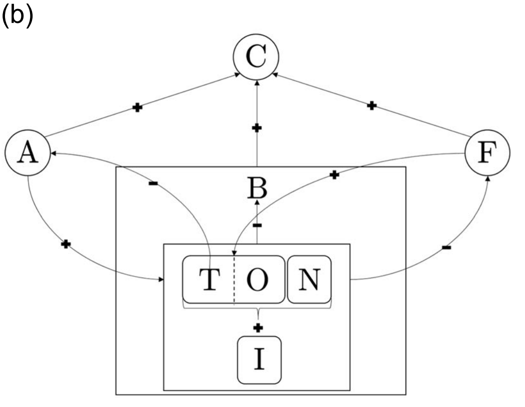
Climate change is a major challenge for humankind and has been termed the "greatest market failure the world has ever seen" (Stern, 2007, p. viii). Consequently, the economic implications of it have been studied extensively over the last decades. In contrast, the economics of ocean acidification, a phenomenon caused by uptake of atmospheric carbon dioxide (CO_2) in the oceans, is still a rather underdeveloped research area. Nevertheless, the socioeconomic consequences of ocean acidification are expected to be considerable. Under a business as usual emission path, ocean acidification is likely to affect ecosystem services provided by the oceans, such as ocean carbon uptake, coastal protection, food security, tourism, human health and biodiversity (Gattuso et al., 2015; Hilmi et al., 2012; Hoegh-Guldberg et al., 2007; Rodrigues et al., 2015; Turley & Gattuso, 2012).

While the largest emitters of greenhouse gas emissions are developed economies, developing economies will likely be hit the hardest by climate change. The same is true for ocean acidification: The highest risk of possible impacts is projected to occur in developing coastal economies, such as Senegal and Madagascar (Cooley et al., 2012), as they depend on fishery resources for nutrition and as a main source of income. To evaluate socioeconomic effects of ocean acidification and design appropriate policy instruments it is constructive to analyze ocean acidification within a broader context of global environmental and ecosystem change (Riebesell & Gattuso, 2015; Turley & Gattuso, 2012). Moreover, ocean acidification is often regionally intensified by local sources of acidification, most importantly through eutrophication caused by nutrient run-off of acidic fertilizers used in agricultural production (Kelly et al., 2011).

Based on these stylized facts of ocean acidification research, this paper describes an economy that is representative of many sea-bordering developing countries, namely highly dependent on agriculture and fisheries and suffering from three negative externalities: global warming, global ocean acidification, and local acidification caused by nutrient run-off of acidic fertilizers used in agricultural production. We design a general equilibrium model to study the interaction of the three negative externalities and appropriate optimal policy responses. For the



Schematic representation of the model.



Model structure and feedback loops.

FIGURE 1 (a) The setting of the model analyzed in this paper. (b) The structure and feedback loops in the economy-environment system, while "+" and "−" reflect the sign of the feedback. The agriculture (A) and fisheries (F) production sectors provide food to consumers (C) and interact with the natural environment; the latter determines environmental quality (B) and is affected by the mean global temperature increase (T), ocean acidification (O), nutrient run-off (N) and their interaction (I)

realistic case of an optimal carbon tax that internalizes the negative effects of global warming and ocean acidification can not be implemented, we also derive a second-best optimal tax on nutrient run-off and compare it to the first-best case. Specifically we ask, if a national economy does not sufficiently internalize global warming and ocean acidification, how can other national policy instruments that in our case focus on local euthrophication help to tackle interacting externalities? Our model tries to grapple with the common challenge that first-best policies are often not possible, and suggest what second-best options might achieve. We find that, for the analyzed setting of a developing coastal economy, an economically optimal policy response to ocean acidification should not only take into account the direct marginal damages from CO_2 emissions but also the marginal damages arising from the interaction with regional nutrient run-off. Our results show that, besides a carbon tax, the implementation of a separate tax on nutrient run-off is advisable.[1] In a second-best setting such a tax would compensate for those damages not internalized by the national carbon tax. Our aim is to capture some of the latest insights of research on ocean acidification within a standard and analytically tractable economic model. We thereby contribute to a better understanding of the social cost of ocean acidification in developing coastal economies, which has been identified as an important avenue for research (Brander et al., 2012; Cooley et al., 2012; Narita et al., 2012).

The remainder of this paper is structured as follows. Section 2 describes the overall structure and feedback loops in the modeled economy-environment system, while it reviews relevant notions and insights from other studies. Section 3 presents the general equilibrium model and derives first- and second-best policy rules. Section 5 summarizes the results and concludes.

[1]We abstain here from complicating issues like non-point sources of pollution (Russell & Shogren, 1993; Xepapadeas, 2011), and assume a single tax, for example, on fertilizers, whose use has a proportional relationship with emissions, is effective. Section 4 discusses some aspects of non-point source pollution in relation to our study.

2 | FRAMEWORK AND RELATED LITERATURE

Figure 1 sketches (a) the setting and (b) the structure and feedback loops in the economy-environment system we analyze in this paper.

The model structure reflects the stylized economic setting of a coastal economy with two producing sectors: Agriculture (A) and fisheries (F). Consumers (C) depend on agricultural and fishery products for nutrition and can thus be expected to be highly exposed to risks from shortages in food supply (Cooley et al., 2012). Consumers and both sectors interact with their natural environment determining regional environmental quality (B) that is assumed to have a positive influence on the well-being of consumers in the economy. In line with previous studies (Baumgärtner et al., 2015; Drupp, 2018; Hoel & Sterner, 2007) we incorporate environmental quality at a very aggregate level relating to all services provided by the natural environment that humans value, ranging from clean water to aesthetic beauty. Environmental quality is represented by the biggest rectangle in Figure 1b and is modelled to be negatively affected by three environmental stressors: The mean global temperature increase (T), ocean acidification (O), nutrient run-off (N) from agricultural production and their interaction (I).

On the one hand we assume that agricultural and fishery production is fossil fuel intensive (FAO, 2019)[2] and hence, contributes to global warming.[3] On the other hand both sectors suffer from increasing CO_2 levels[4] that not only lead to global warming,[5] but also to "the other" CO_2 problem (Doney et al., 2009) caused by the uptake of CO_2 by the world's oceans, namely ocean acidification.[6] Global warming has been found to have negative effects on both agriculture[7] and fisheries.[8] While scenarios with high precipitation and increased temperatures may be beneficial for agriculture in certain Nordic regions, such as Canada and Russia, models simulating agricultural impacts suggest that even moderate global warming could already have negative effects on wheat, maize and rice production of subsistence farmers operating in many developing coastal economies (Morton, 2007). Socioeconomic consequences for fisheries are expected in particular for coastal fishing communities (Cheung et al., 2013), which are a central element of the analysis in this paper. In our model both the agricultural and the fishery sector positively contribute to ocean acidification, but only the fishery sector, which depends on ocean resources, is negatively affected by it. The increase in seawater acidity could lead to important negative effects on the growth of calcifying organisms (Kroeker et al., 2010), but also for noncalcifying fish species (Frommel et al., 2012; Stiasny et al., 2016) implying negative ecological and economic impacts (Cooley & Doney, 2009; Gattuso, 2014; Voss et al., 2015, 2019). Direct impacts on fisheries markets may occur because commercially important global fish populations could decline (Cooley & Doney, 2009; Hänsel et al., 2020; Talmage & Gobler, 2010; Voss et al.,

[2] We assume that fossil fuels are needed to run tractors and fishing boats. In developing coastal economies, like Senegal and Madagascar, greenhouse gas emissions from agriculture and land use accounted for 63.8% (Senegal) and 89.2% (Madagascar) of total emissions in 2010 (FAO, 2019).

[3] Most agricultural greenhouse gas emissions are non-CO_2 emissions, with methane CH_4 due to cattle belching and N_2O due to fertilizers representing the largest sources. A tax on fertilizer use as proposed in this paper could capture both externalities related to run-off and to air (N_2O).

[4] Mostly as a result of fossil fuel emissions and land use changes global mean atmospheric CO_2 levels have increased by 42% from about 280 ppm in preindustrial levels to 405 ppm in the beginning of 2017 (IPCC, 2013; NOAA, 2017).

[5] According to the World Meteorological Organization 2016 was the hottest year on record with 1.1°C above preindustrial levels.

[6] Between 1750 and 2011 the world's oceans have absorbed about 30% of atmospheric CO_2 (IPCC, 2013). With high confidence this has caused ocean surface pH to fall by 0.1 below the preindustrial average, which translates into a 26% increase in acidity (IPCC, 2013). Under business as usual (IPCC AR5, RCP 8.5) ocean surface pH is projected to fall by 0.42 units below preindustrial levels by 2100 (Bopp et al., 2013).

[7] The relationship between crop yields in agriculture and climatic variables is well studied in both developed and developing countries (Burke & Emerick, 2016; Chen et al., 2016; Deschênes & Greenstone, 2007; Mendelsohn et al., 1994; Schlenker et al., 2006; Schlenker & Roberts, 2009; Welch et al., 2010).

[8] Studies that estimate the effect of ocean warming on global fisheries predict spatial redistribution effects of fisheries catch potential (Blanchard et al., 2012; Cheung et al., 2010), higher vulnerability of coastal fisheries to climate change (Allison et al., 2009) and changes in catch composition (Cheung et al., 2013).

2015, 2019). In addition, nonmarket impacts are possible due to restructuring of ecosystems, biodiversity loss and degradation of coral reefs (Gattuso et al., 2015; Hilmi et al., 2012; Hoegh-Guldberg et al., 2007; Rodrigues et al., 2015).

The existing literature on the economic impacts of—and appropriate policy responses to—global warming and ocean acidification mainly studies either effect in isolation from one another and from other potential environmental stressors. However, it will be key to understand ocean acidification within a more comprehensive ecosystem response to environmental change (Riebesell & Gattuso, 2015; Turley & Gattuso, 2012). Oftentimes, the effects of global warming and ocean acidification are regionally intensified by specific local sources of acidification like sulfur dioxide precipitation or eutrophication through run-off of acidic fertilizers (Kelly et al., 2011). As a consequence, a regional strategy to counteract ocean acidification would have to be designed in a way that integrates impacts from ocean acidification with other global ocean stressors, such as overfishing, habitat destruction, temperature change and nonacidifying pollution, and with specific regional stressors like eutrophication (Kelly et al., 2011). In this paper we build on this by designing a stylized economic setting, which integrates ocean acidification with global warming as a key global environmental stressor as well as with nutrient run-off (N) of acidic fertilizers used in agricultural production as a key regional environmental stressor.

Human inputs of nutrients such as nitrogen and phosphorus, which are used in agricultural fertilization to increase food output, can result in excessive production of algae. This process, known as eutrophication, changes the structure and functioning of global ecosystems and its services provided to humans (Compton et al., 2011; Diaz & Rosenberg, 2008; Rockstrom et al., 2009). The microbial decomposition of the large phytoplancton biomass originating from algae booms not only results in low oxigen concentrations (hypoxia), which can displace or kill fish and invertebrates populations. At the same time this process releases CO_2, which lowers the pH and increases the acidity of subsurface waters in coastal regions (Cai et al., 2011). In some regions coastal eutrophication contributes more to coastal water acidity than global ocean acidification (Kelly et al., 2011). In addition euthrophication may reduce the ability of coastal waters to buffer changes in pH, such that the interaction of global and coastal ocean acidification is more than the sum of both effects (Cai et al., 2011). In our model, we account for this by including an interaction effect (I) between temperature, ocean acidification and nutrient run-off. While the agricultural sector only suffers from temperature damages, fisheries are negatively affected by all three modelled negative externalities and their interaction. The interaction effect could both reflect a conceptually different externality or simply that the overall externality can become larger than the sum of the pure externality effects of each type as suggested by Cai et al. (2011). In the latter case the interaction effect is more about the size than the nature of the effect.

We utilize the model structure in Figure 1b to find optimal national policy responses to (i) the negative effects of carbon in the atmosphere (global warming and ocean acidification) and (ii) nutrient run-off in general equilibrium. Although an effective internalization of CO_2 externalities based on an optimal carbon tax should be the ultimate target to fight both global warming and ocean acidification, this is far from being realistic. It has been argued that the missing political willingness to support a global solution can be a reason to focus more on regional management (Rau et al., 2012). Existing global effort will not be enough to prevent marine ecosystems from serious changes and hence, regional tailor-made mitigation strategies particularly targeting those, which are most affected (e.g., small developing coastal communities), should receive more attention (Rau et al., 2012; Strong et al., 2014). In this light, we not only calculate the first-best optimal taxes on carbon and nutrient run-off, but also derive the second-best optimal tax on nutrient run-off for the case that an effective internalization of CO_2 externalites is lacking.

Some elements of our modelling approach connect to the literature on second-best policies in the trade and environment literature (Krutilla, 1991; Markusen, 1975). While Markusen (1975) extends the theory of corrective taxation when only one instrument is available to deal with multiple externalities simultaneously, Krutilla (1991) focuses on second-best environmental taxes in the presenence of trade-effects in an an open economy. We also build on the literature on regulation of multiple pollutants that interact in terms of environmental damages and abatement costs (Ambec & Coria, 2013, 2018; Caplan & Silva, 2005; Endres, 1985; Fullerton & Karney, 2018; Legras, 2011; Moslener & Requate, 2007; Repetto, 1987) or through markets (Ren et al., 2011). Early studies like Endres (1985) and Repetto (1987) focus on the control of several pollutants in a static framework while Moslener & Requate (2007) look at optimal abatement when pollutants interact dynamically. The latter find that the dynamic properties of the pollutants as well as whether they concern technological substitutes or complements influence optimal emission pathways. Caplan and Silva (2005) analyze "correlated externalities" resulting from multiple pollutants within a multistage game theoretic framework. Ambec and Coria (2018) address policy-spillovers when regulating trans-boundary and local pollutants. In terms of methodological approach, Fullerton and Karney (2018) and Ren et al. (2011) are closest to our study. The first employ a two-sector, two-pollutant, theoretical general equilibrium model showing distinct welfare effects of taxes versus permits. Ren et al. (2011) develop a theoretical general equilibrium model to analyze the interaction of greenhouse gas emissions and nitrogen leaching as environmental externalities originating from fossil fuel and biofuel production. Because the two fuel types are substitutes in the market, taxing one of them influences the level of emissions from the other externality. While they find this effect to be ambiguous, the authors also calculate a second-best externality tax that may be higher or lower than the first-best tax, depending on the elasticity of substitution between the products that generate the two externalities.

Our study differs from this literature in various ways. First our paper is about the economics of ocean acidification rather than a general, methodological contribution on the optimal regulation of multiple pollutants. We take the latest research on ocean acidification as a starting point and design a model that captures relevant stylized facts. This involves conceptualizing the economics of ocean acidification in interaction with other global and regional environmental stressors—in particular global warming and euthrophication—to develop an integrated policy response as well as focusing on economies that are most affected by this combination of stressors. We make use of a general equilibrium structure to analyze the case when the marginal social damages of ocean acidification and global warming are not fully covered by a carbon tax and derive a second-best tax on euthrophication for this case. In contrast to Ren et al. (2011), we are able to analytically show that the second-best nutrient tax will always be higher than the first-best optimal tax that covers the marginal social damage from euthrophication. Our paper's contribution to the literature on the economics of ocean acidification is therefore twofold. First we provide a clear analytic model that captures the essentials of a setting that is most relevant regarding damages from ocean acidification. Second, we highlight that regional environmental policy aimed at preventing regional acidification resulting from euthrophication could help in tackling the severity of the global acidification problem, thus underlining the need for regional management as pointed out in Rau et al. (2012).

3 | MODEL AND POLICY RULES

3.1 | The general equilibrium model

We introduce a static general equilibrium model of a closed coastal economy with agriculture (A) and fisheries (F) as production sectors, which generate three externalities. CO_2 emissions contribute to global warming, captured in the model by an increase of atmospheric temperature (T) relative to the preindustrial level. CO_2 emissions further cause ocean acidification (O). A third externality is due to agriculture run-off of fertilizers which cause eutrophication (N for nutrient run-off) of the ocean. We assume that agricultural output is only affected by global warming. On the other hand the fisheries sector suffers from all three externalities, due to global warming, ocean acidification and eutrophication. Moreover, we include an interaction term (I) to reflect that the three effects may be synergetic in terms of the overall damage.

The two sectors produce output Q^i (with $i = A, F$) by means of emissions and labor.[9] We assume that variable inputs like fertilizers or fuels are perfectly correlated with capital use, such as tractors or fishing boats. Thus, while capital utilization is carbon (M) emission intensive, with e_M^A and e_M^F denoting carbon emissions in the agriculture and fishery sector, emissions from eutrophication e_N^A can be thought of to be a byproduct of capital utilization in the agriculture sector.

Net output in the agricultural sector Q^A increases in labor l^A, agricultural carbon emissions e_M^A and emissions from nutrient run-off e_N^A. Q^A decreases in the global mean atmospheric temperature increase T, which determines temperature damages.

$$Q^A = f^A\left(l^A, e_M^A, e_N^A, T\right) \tag{1}$$

Additionally we assume that f^A is strictly concave in carbon emissions, that is, that $\frac{\partial^2 f^A}{\partial e_M^A \partial e_M^A} < 0$ and that the second cross derivative is positive, that is, $\frac{\partial^2 f^A}{\partial e_M^A \partial e_N^A} > 0$. The former means that carbon emissions become less productive the more carbon emissions are needed for production. The latter captures that carbon emissions and nutrient run-off are modeled as complements, reflecting that carbon-intensive fuels as well as acidic fertilizers are jointly used in agricultural production.[10]

Net output in the fishery sector Q^F increases in labor l^F and carbon emissions e_M^F and decreases in the global mean temperature anomaly T, ocean acidification O, nutrient run-off N and in an interaction effect I determined by all three environmental stressors. Specifically, the interaction term captures synergetic environmental damage in line with the literature (Cai et al., 2011; Kelly et al., 2011) discussed in Section 2.

To make the model as simple and tractable as possible, we abstract from the traditional representation of bio-economic fisheries productions functions with fishing effort and fish biomass as input factors, but instead focus on labor and capital as the limiting economic factors in production. Specifically, fishing effort can be viewed as being produced by labor and capital, while the latter is correlated with fuel usage.[11]

[9] In line with the literature on optimal pollution regulation (e.g Muller and Mendelsohn 2009) we treat emissions directly as a factor of production.

[10] The cross derivative is negative when the production factors are substitutes. See Hoel (2012) for an example of energy production from fossil fuels and renewables.

[11] Labor and capital (i.e., fishing boats size correlated with fuel use) are substitutes in the production of fishing effort. For example the same level of fishing effort could be achieved by a large number of fisherman (high labor) and handline fishing from a small boat (low capital, low fuel usage) or by a small number of fisherman (low labor) working on a big trawler (high capital and fuel usage).

$$Q^F = f^F\left(l^F, e_M^F, T, O, N, I\right) \tag{2}$$

In terms of factors of production, we assume an inelastic factor supply (Goldberg, 2016). Total carbon emissions E_M are the sum of carbon emissions from both sectors of the economy and carbon emissions from the rest of the world e_M^R. Total emissions from nutrient run-off E_N are the sum of nutrient emissions from agricultural production and nutrient run-off from the rest of the world e_M^R.

$$L = l^A + l^F \tag{3}$$

$$E_M = e_M^A + e_M^F + e_M^R \tag{4}$$

$$E_N = e_N^A + e_N^R \tag{5}$$

We focus on a representative consumer, who derives utility from the consumption of agricultural and fish products C^A and C^F as well as from a public good B representing environmental quality. This is in line with previous studies that incorporate an aggregate environmental good in the utility function (Baumgärtner et al., 2015; Drupp, 2018; Hoel & Sterner, 2007). The inclusion of environmental quality in the utility function reflects that there are not only direct use values of land and ocean based ecosystems but also nonuse values. Utility increases in B while we model B to be negatively affected by the three environmental stressors and their interaction. The resulting utility function can be represented as

$$U\left(c^A, c^F, B(T, O, N, I)\right). \tag{6}$$

Finally, the output in both sectors of the economy is consumed entirely.[12]

$$Q^i = c^i \quad \text{with} \quad i = A, F \tag{7}$$

Both the global mean atmospheric temperature increase T and ocean acidification O increase in the total amount of carbon emissions E_M.

$$T = T(E_M) \quad \text{with} \quad T' > 0 \tag{8}$$

$$O = O(E_M) \quad \text{with} \quad O' > 0 \tag{9}$$

Eutrophication is caused by the total amount of nutrient run-off N, which increases in the total amount of nutrient run-off due to fertilizer use in the agricultural and fishery sector E_N.

$$N = N(E_N) \quad \text{with} \quad N' > 0 \tag{10}$$

The interaction effect I increases in both total carbon emissions and total emissions from nutrient run-off.

$$I = I(E_M, E_N) \quad \text{with} \quad \frac{\partial I}{\partial E_M} > 0, \quad \frac{\partial I}{\partial E_N} > 0 \quad \text{and} \quad \frac{\partial I}{\partial E_N \partial E_M} > 0 \tag{11}$$

In the following we will first derive the model's market solution capturing the utility- and profit-maximizing behavior of consumers and firms while disregarding externalities. In a second step we take the perspective of a representative benevolent government in a developing

[12]This condition also implies that a household can become both a consumer and a producer, which is often the case in developing countries.

coastal economy that maximizes well-being while taking into account external effects through environmental damage. Comparing the resulting socially optimal allocation to the market solution allows us to derive specific policy rules that internalize externalities to achieve maximum social welfare. The following table summarizes the notation in our model.

	Summary of model notation
$Q^i, i = A, F$	Production output in agriculture (A) and fisheries (F)
$e_M^i, i = A, F, R$	Carbon emissions in agriculture (A), fisheries (F) and rest of the world (R)
E_M	Total carbon emissions
$e_N^i, i = A, R$	Emissions from nutrient run-off acidic fertilizers used in national agriculture (A) and in the rest of the world (R)
E_N	Total emissions from nutrient run-off
$l^i, i = A, F$	Labor in agriculture (A) and fisheries (F)
L	Total amount of labor
$T(E_M)$	Global mean temperature increase
$O(E_M)$	Ocean acidification
$N(E_N)$	Nutrient run-off
$I(E_M, E_N)$	Interaction effect between T, O, and N
$B(T, O, N, I)$	Environmental quality
$f^A\left(l^A, e_M^A, e_N^A, T\right)$	Agricultural production function
$f^F\left(l^F, e_M^F, T, O, N, I\right)$	Fisheries production function
$c^i, i = A, F$	Consumption of agricultural (A) and fishery products (F)
$U(c^A, c^F, B)$	Utility function of the representative consumer

3.2 | Market solution

The representative consumer maximizes utility subject to a budget constraint, where w is the wage, p^F is the price of the final food produced in the fishery sector, while we set the price of the agricultural good to unity, that is, $p^A = 1$ (numeraire).

$$\max_{\{c^A, c^F\}} U(c^A, c^F, B) \quad \text{subject to} \quad wL \geq c^A + p^F c^F \tag{12}$$

In the optimum the marginal rate of substitution between consumption of agricultural products c^A and fish consumption c^F is equal to the price ratio of the two products, that is:

$$\frac{\partial U/\partial c^A}{\partial U/\partial c^F} = \frac{1}{p^F} \tag{13}$$

In each sector the representative firms maximizes profits subject to the production technology. Production costs include the payment of taxes τ_M on carbon emissions and τ_N on nutrient run-off.

$$\max_{\left\{l^A, e_M^A, e_N^A\right\}} \left\{ f^A\left(l^A, e_M^A, e_N^A, T\right) - wl^A - \tau_M e_M^A - \tau_N e_N^A \right\} \tag{14}$$

$$\max_{\left\{l^F, e_M^F\right\}} \left\{ p^F f^F\left(l^F, e_M^F, T, O, N, I\right) - wl^F - \tau_M e_M^F \right\} \tag{15}$$

The first-order conditions for both sectors are then:

$$\frac{\partial f^A}{\partial l^A} = w \tag{16}$$

$$\frac{\partial f^A}{\partial e_M^A} = \tau_M \tag{17}$$

$$\frac{\partial f^A}{\partial e_N^A} = \tau_N \tag{18}$$

$$\frac{p^F \partial f^F}{\partial l^F} = w \tag{19}$$

$$\frac{p^F \partial f^F}{\partial e_M^F} = \tau_M \tag{20}$$

We can equate (16) with (19) and (17) with (20) to arrive at the following two conditions:

$$\frac{\partial f^A}{\partial l^A} = \frac{p^F \partial f^F}{\partial l^F} \tag{21}$$

$$\frac{\partial f^A}{\partial e_M^A} = \frac{p^F \partial f^F}{\partial e_M^F} \tag{22}$$

Equations (21) and (22) require that in equilibrium both the value of the marginal product of labor and the value of the marginal product of carbon emissions must be the same in the two sectors. The value of the marginal product of carbon emissions can also be interpreted as the cost the representative firm has to bear when abating one unit of carbon emissions. Hence, (22) can be interpreted as one of the cfundamental insights of environmental economics: In the equilibrium with pollution taxation marginal abatement cost must be equal across sectors. This result is due here to a uniform carbon tax, regardless of its specific value. From the first order conditions (17) and (20) we know that the optimal carbon tax must be exactly equal to the marginal abatement cost of carbon emissions. Similarly, (18) requires that the optimal tax on nutrient run-off from agricultural production equates to the marginal abatement cost of nutrient emissions.

Finally we can combine Equation (13) with Equations (21) and (22):

$$\frac{\frac{\partial U}{\partial c^A}}{\frac{\partial U}{\partial c^F}} = \frac{\frac{\partial f^F}{\partial l^F}}{\frac{\partial f^A}{\partial l^A}} = \frac{\frac{\partial f^F}{\partial e_M^F}}{\frac{\partial f^A}{\partial e_M^A}} \tag{23}$$

This means that the marginal rate of substitution between agricultural product consumption and fish consumption must equal the marginal rate of technical substitution between labor in the two sectors, which must again be equal to the marginal rate of technical substitution between carbon emissions used in production in each of the sectors.

3.3 | Socially optimal allocation

We now assume a benevolent government that maximizes social welfare in the developing coastal economy. Specifically, this central planner maximizes the utility of a representative agent, while taking into consideration the entire feedback structure in the economy. The resulting optimization program reads:

$$\max_{\left\{c^A, c^F, l^A, l^F, e_M^A, e_M^F, e_N^A\right\}} (6) \quad \text{subject to} \quad (1), (2), (3), (4), (5), (7), (8), (9), (10), (11) \tag{24}$$

By substituting all the constraints into the objective function, the following maximization problem results:[13]

$$\begin{aligned} &\max_{\left\{l^A, e_M^A, e_M^F, e_N^A\right\}} U f^A\Big(l^A, e_M^A, e_N^A, T(E_M)\Big), \\ &f^F\Big(L - l^A, e_M^F, T(E_M), O(E_M), N(E_N), I(E_M, E_N)\Big), \\ &B\Big(T(E_M), O(E_M), N(E_N), I(E_M, E_N)\Big) \end{aligned} \tag{25}$$

The first-order conditions[14] describing the socially optimal allocation are:

$$\begin{aligned} &\frac{\partial U}{\partial e_M^A} = 0 \quad \Leftrightarrow \quad \frac{\partial U}{\partial c^A}\left[\frac{\partial f^A}{\partial e_M^A} + \frac{\partial f^A}{\partial T}T'\right] + \frac{\partial U}{\partial c^F}\left[\frac{\partial f^F}{\partial T}T' + \frac{\partial f^F}{\partial O}O' + \frac{\partial f^F}{\partial I}\frac{\partial I}{\partial e_M^A}\right] \\ &+\frac{\partial U}{\partial B}\left[\frac{\partial B}{\partial T}T' + \frac{\partial B}{\partial O}O' + \frac{\partial B}{\partial I}\frac{\partial I}{\partial e_M^A}\right] = 0 \end{aligned} \tag{26a}$$

$$\begin{aligned} &\frac{\partial U}{\partial e_M^F} = 0 \quad \Leftrightarrow \quad \frac{\partial U}{\partial c^A}\left[\frac{\partial f^A}{\partial T}T'\right] + \frac{\partial U}{\partial c^F}\left[\frac{\partial f^F}{\partial e_M^F} + \frac{\partial f^F}{\partial T}T' + \frac{\partial f^F}{\partial O}O' + \frac{\partial f^F}{\partial I}\frac{\partial I}{\partial e_M^F}\right] \\ &+\frac{\partial U}{\partial B}\left[\frac{\partial B}{\partial T}T' + \frac{\partial B}{\partial O}O' + \frac{\partial B}{\partial I}\frac{\partial I}{\partial e_M^F}\right] = 0 \end{aligned} \tag{26b}$$

$$\frac{\partial U}{\partial e_N^A} = 0 \quad \Leftrightarrow \quad \frac{\partial U}{\partial c^A}\frac{\partial f^A}{\partial e_N^A} + \frac{\partial U}{\partial c^F}\left[\frac{\partial f^F}{\partial N}N' + \frac{\partial f^F}{\partial I}\frac{\partial I}{\partial e_N^A}\right] + \frac{\partial U}{\partial B}\left[\frac{\partial B}{\partial N}N' + \frac{\partial B}{\partial I}\frac{\partial I}{\partial e_N^A}\right] = 0 \tag{26c}$$

[13]Note that an equivalent approach to solving the maximization problem of the central planner would be to first characterize utility-maximizing consumption choices and then let the central planner maximize the resulting indirect utility function of the representative consumer.

[14]Note that $\frac{\partial T}{\partial e_M^A} = \frac{\partial T}{\partial e_M^F} = T'$, $\frac{\partial O}{\partial e_M^A} = \frac{\partial O}{\partial e_M^F} = O'$, $\frac{\partial N}{\partial e_N^A} = N'$.

$$\frac{\partial U}{\partial l^A} = 0 \quad \Leftrightarrow \frac{\partial U}{\partial c^A}\frac{\partial f^A}{\partial l^A} - \frac{\partial U}{\partial c^F}\frac{\partial f^F}{\partial l^F} = 0 \tag{26d}$$

From (26d) we obtain the well known condition for the socially optimal allocation in the private good markets, which is identical to (23).

$$\frac{\frac{\partial U}{\partial c^A}}{\frac{\partial U}{\partial c^F}} = \frac{\frac{\partial f^F}{\partial l^F}}{\frac{\partial f^A}{\partial l^A}} \tag{27}$$

The marginal rate of substitution between agricultural product consumption and fish consumption must equal the marginal rate of technical substitution between labor in the two markets.

We rearrange (26a) and use (17) to obtain the optimal tax on carbon emissions τ_M^*, which is equal to the Pigouvian carbon tax $\widehat{\tau_M}^*$ capturing the marginal social damage from carbon emissions.[15]

$$\begin{aligned}
\tau_M^* = \widehat{\tau_M}^* = & \Bigg[\overbrace{-\frac{\partial U}{\partial B}\left(\frac{\partial B}{\partial T}T' + \frac{\partial B}{\partial O}O' + \frac{\partial B}{\partial I}\frac{\partial I}{\partial e_M^A}\right)}^{\text{MD Environmental quality}} \overbrace{-\frac{\partial U}{\partial c^A}\frac{\partial f^A}{\partial T}T'}^{\text{MD Agriculture}} \\
& \overbrace{-\frac{\partial U}{\partial c^F}\left(\frac{\partial f^F}{\partial T}T' + \frac{\partial f^F}{\partial O}O' + \frac{\partial f^F}{\partial I}\frac{\partial I}{\partial e_M^A}\right)}^{\text{MD Other-Sector}} \Bigg] \frac{1}{\frac{\partial U}{\partial c^A}} \\
= & \Bigg[\overbrace{\left(-\frac{\partial U}{\partial B}\frac{\partial B}{\partial T} - \frac{\partial U}{\partial c^A}\frac{\partial f^A}{\partial T} - \frac{\partial U}{\partial c^F}\frac{\partial f^F}{\partial T}\right)T'}^{\text{MD Temperature}} + \overbrace{\left(-\frac{\partial U}{\partial B}\frac{\partial B}{\partial O} - \frac{\partial U}{\partial c^F}\frac{\partial f^F}{\partial O}\right)O'}^{\text{MD Ocean Acidification}} \\
& + \overbrace{\left(-\frac{\partial U}{\partial B}\frac{\partial B}{\partial I} - \frac{\partial U}{\partial c^F}\frac{\partial f^F}{\partial I}\right)\frac{\partial I}{\partial e_M^A}}^{\text{MD Interaction}} \Bigg] \frac{1}{\frac{\partial U}{\partial c^A}}
\end{aligned} \tag{28}$$

Equation (28) shows two decompositions, allowing two interpretations of the optimal tax. According to the first decomposition (first and second line in Equation 28) the optimal carbon tax is the sum of marginal damages (MD) from temperature increase, ocean acidification, nutrient run-off and the interaction term measured in terms of consumption of the agricultural sector. The second decomposition (third and forth line in Equation 28) illustrates that the optimal tax includes marginal damages on environmental quality as well as marginal damages on production in the agricultural sector and the fishery sector.

To calculate the optimal tax on nutrient run-off τ_N^*, we use (18) and rearrange (26c).

[15] Note that the Pigouvian tax must not always be equal to the optimal tax, see for example Cremer et al. (1998).

$$\tau_N^* = \widehat{\tau_N}^* = \left[\overbrace{-\frac{\partial U}{\partial B}\left(\frac{\partial B}{\partial N}N' + \frac{\partial B}{\partial I}\frac{\partial I}{\partial e_N^A}\right)}^{\text{MD Environmental quality}} - \overbrace{\frac{\partial U}{\partial c^F}\left(\frac{\partial f^F}{\partial N}N' + \frac{\partial f^F}{\partial I}\frac{\partial I}{\partial e_N^A}\right)}^{\text{MD Fisheries}} \right] \frac{1}{\frac{\partial U}{\partial c^A}}$$
$$= \left[\overbrace{\left(-\frac{\partial U}{\partial B}\frac{\partial B}{\partial N} - \frac{\partial U}{\partial c^F}\frac{\partial f^F}{\partial N}\right)N'}^{\text{MD Nutrient-Runoff}} + \overbrace{\left(-\frac{\partial U}{\partial B}\frac{\partial B}{\partial I} - \frac{\partial U}{\partial c^F}\frac{\partial f^F}{\partial I}\right)\frac{\partial I}{\partial e_N^A}}^{\text{MD Interaction}} \right] \frac{1}{\frac{\partial U}{\partial c^A}} \tag{29}$$

The optimal tax on nutrient run-off τ_N^* (29) is equal to its Pigouvian level $\widehat{\tau_N}^*$ that internalizes the marginal social damage from nutrient run-off in agricultural production. It is the sum of marginal damages from nutrient run-off and marginal damages from the interaction of nutrient run-off with temperature and ocean acidification. The tax reflects marginal damages from nutrient run-off on environmental quality and on production in the fishery sector.

3.4 | Second best optimal allocation

We assume now that the social planner cannot implement the carbon tax at the Pigouvian level and hence, there is no effective internalization of CO_2 damages. This could, for example, be due to the difficult task of estimating marginal economic damages from carbon emissions in the developing coastal economy, missing political willingness to support an optimal policy rule or due to a lacking effective international agreement to harmonize policies, which allows countries to implement serious national climate policies. Given a carbon tax that falls short of internalizing the full marginal damages from carbon emissions, this section elaborates if regional environmental policy in form of a tax on nutrient could compensate for unregulated carbon emissions. Based on the literature analyzed in Section 2, we seek to provide a formal economic argument for the importance of regional management of ocean acidification, that is often intensified by regional nutrient-runoff from agricultural production.

Formally the carbon tax is exogenous in this case such that the second-best optimal level of emissions from nutrient run-off is the value of e_N^A that satisfies (25), while $e_M^A = \widehat{e_M^A}\left(l^A, e_N^A, T, \tau_M\right)$ and $e_M^F = \widehat{e_M^F}(L - l^A, T, O, N, I, \tau_M)$ are implicitly[16] defined by (17) and (20). The intuition is that in each sector the representative firm will choose its level of carbon emission once the government defines the carbon tax. Hence, the optimization program determining this second-best allocation reads:

$$\max_{\left\{l^A, \widehat{e_M^A}, \widehat{e_M^F}, e_N^A\right\}} U f^A\left(l^A, \widehat{e_M^A}, e_N^A, T\left(\widehat{e_M^A} + \widehat{e_M^F} + e_M^R\right)\right),$$
$$f^F\left(L - l^A, \widehat{e_M^F}, T\left(\widehat{e_M^A} + \widehat{e_M^F} + e_M^R\right), O\left(\widehat{e_M^A} + \widehat{e_M^F} + e_M^R\right), N(E_N), I\left(\widehat{e_M^A} + \widehat{e_M^F} + e_M^R, E_N\right)\right), \tag{30}$$
$$B\left(T\left(\widehat{e_M^A} + \widehat{e_M^F} + e_M^R\right), O\left(\widehat{e_M^A} + \widehat{e_M^F} + e_M^R\right), N(E_N), I\left(\widehat{e_M^A} + \widehat{e_M^F} + e_M^R, E_N\right)\right)$$

[16] We make use of the implicit function theorem here.

The second-best tax on nutrient run-off is optimally determined by the following first-order condition:[17]

$$\begin{aligned}\frac{\partial U}{\partial e_N^A} = 0 \quad \Leftrightarrow \quad & \frac{\partial U}{\partial c^A}\left[\frac{\partial f^A}{\partial e_M^A}\frac{\partial \widehat{e_M^A}}{\partial e_N^A} + \frac{\partial f^A}{\partial e_N^A} + \frac{\partial f^A}{\partial T}T'\frac{\partial \widehat{e_M^A}}{\partial e_N^A}\right] \\ & + \frac{\partial U}{\partial c^F}\left[\frac{\partial f^F}{\partial T}T'\frac{\partial \widehat{e_M^A}}{\partial e_N^A} + \frac{\partial f^F}{\partial O}O'\frac{\partial \widehat{e_M^A}}{\partial e_N^A} + \frac{\partial f^F}{\partial N}N' + \frac{\partial f^F}{\partial I}\left(\frac{\partial I}{\partial e_M^A}\frac{\partial \widehat{e_M^A}}{\partial e_N^A} + \frac{\partial I}{\partial e_N^A}\right)\right] \\ & + \frac{\partial U}{\partial B}\left[\frac{\partial B}{\partial T}T'\frac{\partial \widehat{e_M^A}}{\partial e_N^A} + \frac{\partial B}{\partial O}O'\frac{\partial \widehat{e_M^A}}{\partial e_N^A} + \frac{\partial B}{\partial N}N' + \frac{\partial B}{\partial I}\left(\frac{\partial I}{\partial e_M^A}\frac{\partial \widehat{e_M^A}}{\partial e_N^A} + \frac{\partial I}{\partial e_N^A}\right)\right] = 0\end{aligned} \tag{31}$$

Using (18) we obtain the second-best optimal tax on nutrient run-off $\widehat{\tau_N}$:

$$\begin{aligned}\widehat{\tau_N} = \Bigg[& \overbrace{-\frac{\partial U}{\partial B}\left(\frac{\partial B}{\partial T}T'\frac{\partial \widehat{e_M^A}}{\partial e_N^A} + \frac{\partial B}{\partial O}O'\frac{\partial \widehat{e_M^A}}{\partial e_N^A} + \frac{\partial B}{\partial N}N' + \frac{\partial B}{\partial I}\left(\frac{\partial I}{\partial e_M^A}\frac{\partial \widehat{e_M^A}}{\partial e_N^A} + \frac{\partial I}{\partial e_N^A}\right)\right)}^{\text{MD Environmental quality}} \\ & \overbrace{-\frac{\partial U}{\partial c^F}\left(\frac{\partial f^F}{\partial T}T'\frac{\partial \widehat{e_M^A}}{\partial e_N^A} + \frac{\partial f^F}{\partial O}O'\frac{\partial \widehat{e_M^A}}{\partial e_N^A} + \frac{\partial f^F}{\partial N}N' + \frac{\partial f^F}{\partial I}\left(\frac{\partial I}{\partial e_M^A}\frac{\partial \widehat{e_M^A}}{\partial e_N^A} + \frac{\partial I}{\partial e_N^A}\right)\right)}^{\text{MD Fisheries}} \\ & \overbrace{-\frac{\partial U}{\partial c^A}\left(\frac{\partial f^A}{\partial e_M^A}\frac{\partial \widehat{e_M^A}}{\partial e_N^A} + \frac{\partial f^A}{\partial T}T'\frac{\partial \widehat{e_M^A}}{\partial e_N^A}\right)}^{\text{MD Agriculture}}\Bigg]\frac{1}{\frac{\partial U}{\partial c^A}}\end{aligned} \tag{32}$$

The second-best optimal tax on nutrient run-off is the sum of marginal damages on environmental quality from nutrient run-off and its interaction with global warming and ocean acidification as well as from marginal damages on fisheries and agriculture. In the following we compare the second-best optimal tax on nutrient run-off to its Pigouvian level $\widehat{\tau_N}^*$, which captures the external effects of nutrient run-off and of its interaction with global warming and ocean acidification as given in Equation (29). This allows us to decompose $\widehat{\tau_N}^*$ according to the next Equation (33).

$$\begin{aligned}\widehat{\tau_N} = \widehat{\tau_N}^* + \Bigg[& \overbrace{-\frac{\partial U}{\partial B}\left(\frac{\partial B}{\partial T}T'\frac{\partial \widehat{e_M^A}}{\partial e_N^A} + \frac{\partial B}{\partial O}O'\frac{\partial \widehat{e_M^A}}{\partial e_N^A} + \frac{\partial B}{\partial I}\frac{\partial I}{\partial e_M^A}\frac{\partial \widehat{e_M^A}}{\partial e_N^A}\right)}^{\text{Additional MD Environmental quality}} \\ & \overbrace{-\frac{\partial U}{\partial c^F}\left(\frac{\partial f^F}{\partial T}T'\frac{\partial \widehat{e_M^A}}{\partial e_N^A} + \frac{\partial f^F}{\partial O}O'\frac{\partial \widehat{e_M^A}}{\partial e_N^A} + \frac{\partial f^F}{\partial I}\frac{\partial I}{\partial e_M^A}\frac{\partial \widehat{e_M^A}}{\partial e_N^A}\right)}^{\text{Additional MD Fisheries}} \overbrace{-\frac{\partial U}{\partial c^A}\left(\frac{\partial f^A}{\partial T}T'\frac{\partial \widehat{e_M^A}}{\partial e_N^A}\right)}^{\text{Additional MD Agriculture}}\Bigg]\frac{1}{\frac{\partial U}{\partial c^A}} \\ & \overbrace{-\frac{\partial f^A}{\partial e_M^A}\frac{\partial \widehat{e_M^A}}{\partial e_N^A}}^{\text{MAC Agriculture}}\end{aligned} \tag{33}$$

[17]Note that $\frac{\partial \widehat{e_M^A}\left(l^A, e_N^A, T, \tau_M\right)}{\partial e_N^A} = -\frac{\frac{\partial^2 f^A}{\partial e_M^A \partial e_N^A}}{\frac{\partial^2 f^A}{\partial e_M^A \partial e_M^A}} > 0.$

We find two opposing effects that either increase or decrease $\widehat{\tau_N}$ relative to its Pigouvian level $\widehat{\tau_N}^*$. First, as the carbon tax is set below the optimal level, both marginal damages on environmental quality and on production in the agricultural and the fishery sector from temperature increases and ocean acidification are higher compared to when the carbon tax is Pigouvian. The second-best nutrient tax covers these marginal damages in addition to the direct marginal damages from nutrient run-off, which tends to increase the second-best optimal tax on nutrient run-off relative to Pigouvian nutrient taxation. Hence, in the second-best situation also marginal damages from temperature increase on the agricultural sector are considered, which is not the case when the nutrient tax is set at its Pigouvian level. Second, at the same time a carbon tax below its Pigouvian level makes carbon a relatively cheap factor of production thereby decreasing marginal abatement cost of carbon used in agricultural production.

We obtain the following relation between $\widehat{\tau_N}$ and $\widehat{\tau_N}^*$:

$$\hat{\tau_N} \gtrless \hat{\tau_N}^* \quad \text{iff}$$
$$\frac{1}{\frac{\partial U}{\partial c^A}}\left[\overbrace{-\frac{\partial U}{\partial B}\left(\frac{\partial B}{\partial T}T' + \frac{\partial B}{\partial O}O' + \frac{\partial B}{\partial I}\frac{\partial I}{\partial e_M^A}\right)}^{\text{MD from } CO_2 \text{ on Environmental Quality}} \overbrace{-\frac{\partial U}{\partial c^F}\left(\frac{\partial f^F}{\partial T}T' + \frac{\partial f^F}{\partial O}O' + \frac{\partial f^F}{\partial I}\frac{\partial I}{\partial e_M^A}\right)}^{\text{MD from } CO_2 \text{ on Fisheries}} \overbrace{-\frac{\partial U}{\partial c^A}\frac{\partial f^A}{\partial T}T'}^{\text{MD from } CO_2 \text{ on Agriculture}}\right] \gtrless \left[\overbrace{\frac{\partial f^A}{\partial e_M^A} \overset{(18)}{=} \tau_M}^{\text{Carbon Tax Agriculture}}\right] \tag{34}$$

The second-best optimal tax on nutrient run-off $\widehat{\tau_N}$ is higher (lower) than the Pigouvian tax on nutrient run-off τ_N^* iff the additional marginal social damage from carbon emissions on environmental quality and on the production in both sectors are higher (lower) than the carbon tax that must be equal to the marginal abatement cost of carbon according to Equation (18). We find that the sum of these additional marginal damages is exactly equal to the social cost of the negative externalities that are covered by the Pigouvian carbon tax (see Equation 28). Thus, Equation (34) simplifies to:

$$\widehat{\tau_N} \gtrless \widehat{\tau_N}^* \quad \text{iff} \quad \widehat{\tau_M}^* \gtrless \tau_M \tag{35}$$

A carbon tax below the Pigouvian level does not fully internalize the social cost of the negative externalities generated by global warming and ocean acidification. As a consequence, Equation (35) implies that the second-best optimal nutrient tax will always be higher than its Pigouvian level. Figure 2 illustrates how the second-best optimal tax on nutrient run-off depends on the carbon tax τ_M that determines the marginal abatement cost of carbon.

The further the carbon tax is from its Pigouvian level $\widehat{\tau_M}^*$, the higher the second-best tax on nutrient run-off, while the latter will reach a maximum value $max\,\widehat{\tau_N}$ for $\tau_M = 0$. Accepting carbon emissions in agricultural production to fuel machinery like tractors is very cheap without the additional tax expenses and thus, the second-best tax on nutrient run-off, which is a byproduct of agricultural production, needs to account for all additional environmental damages caused by the increased use of carbon emissions in production. The higher τ_M, the lower $\widehat{\tau_N}$ as using carbon emissions in agricultural production becomes more expensive, which lowers the associated environmental damages. When $\tau_M = \widehat{\tau_M}^*$ the social costs of negative externalities are internalized by the Pigouivian carbon tax and the second-best tax on nutrient run-off does not need to cover unregulated CO_2 emissions and hence, will be set at its Pigouvian level $\widehat{\tau_N}^*$.

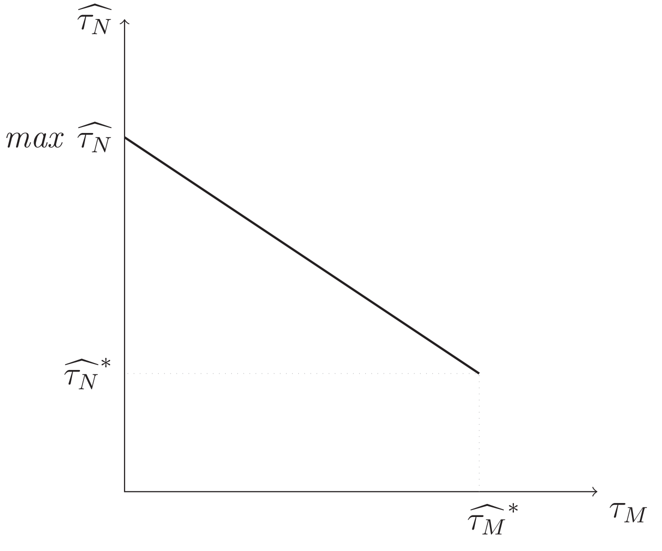


FIGURE 2 Second-best optimal tax on nutrient run-off $\widehat{\tau_N}$ as a function of the carbon tax τ_M

4 | DISCUSSION

This section discusses three main limitations of the theoretical analysis presented in this paper. First, it does not describe eutrophication as a nonpoint source pollution problem, as this would require an explicit spatial approach and hence a very different type of model (Russell & Shogren, 1993; Xepapadeas, 2011), which would make it unsuitable to address the other issues we tackle. To not over-complicate our model, we abstracted from difficulties associated with nonpoint source pollution and include a tax on the use of fertilizers, whose use has a proportional relationship with emissions. This would control the non-point source externality well if it was levied per unit of toxicity-weighted ingredient, which might require the implementation of mineral accounts for each farm in the country so as to record the application of nitrogen to crops (Pearce & Koundouri, 2003). Nitrogen fertilizer taxation has been found to be an effective policy in Austria, Finland, and Sweden (Rougoor et al., 2001). Finger (2012) shows that a nitrogen fertilizer tax would be the more effective the higher farmers' risk aversion. Although fertilizer use in developing countries is rather low compared to developed countries in absolute terms, it grows at a significantly faster rate: The average yearly growth rate of nitrogen use between 2000 and 2018 has been seven times higher in Least Developed Countries compared to the European Union and two to three times higher compared to the United States (FAO, 2021).[18] This is no surprise since developing countries have a high incentive to increase agricultural yields being a major source of their income and nutrition. Thus, on the one hand a tax on fertilizer use has a clear potential to incentivize the application of environmentally friendlier technologies and mitigate eutrophication and its interaction with global warming and ocean acidification at low societal costs. It also creates tax revenues that can be redistributed to farmers to buffer distributional concerns and reduce resistance among farmers. On the other hand, fertilizer taxation can increase food prices and hence alter choices throughout the

[18] In the EU nitrogen use has grown from 84.15 to 90.37 kg/ha of cropland between 2000 and 2018, while it grew from 60.11 to 72.58 kg/ha in the United States. In the same period nitrogen use increased from 10.73 to 17.61 kg/ha in least developed countries.

production-consumption chain, thus allowing for a socially optimal trade-off between mitigating environmental stressors and food security. Implementing such a tax reform would be subject to a number of problems, notably related to political feasibility and imperfect markets. Addressing these barriers through clear communication and interaction with local stakeholders could be key to ensure a just transition to more sustainable agricultural practices.

Second, uncertainty regarding ecosystem responses to ocean acidification in interaction with other stressors is relatively high. Although a large number of studies focusing on physiological responses of calcifying organisms have been published over the last years, the findings are partly contradicting (Meyer & Riebesell, 2015) and uncertainties regarding the organisms' exact sensitivity to ocean acidification remain. For example Kroeker et al. (2013) report that some organisms show enhanced responses to projected future ocean acidification conditions. Moreover, some of the key mechanisms, like calcification, are still not sufficiently understood (Waldbusser et al., 2016). Moreover, uncertainty extends to how such effects for particular organisms and species scale up to the level of marine ecosystems and to what extent these can adapt. Real world policy responses to interacting externalities of ocean acidification, global warming and eutrophication should ideally take such uncertainties regarding marine ecosystem responses to changing environmental conditions into account (Browman, 2016).

Third, our study employs a national general equilibrium model that does not consider how national carbon dioxide emissions affect marginal damages due to temperature increase and ocean acidification in the rest of the world. A sufficiently high global carbon tax, which should be the goal of international negotiations, would take these additional marginal damages into account. Unfortunately, it has been proven extremely difficult to find a global agreement on appropriately regulating carbon dioxide emissions. The Paris Climate Agreement does not specify any consistent policies among countries, but includes merely voluntary pledges for emissions reductions. In such a situation national environmental policy may help those regions that are likely to be most affected by a combination of global warming, ocean acidification and local stressors such as eutrophication (Kelly et al., 2011).

5 | CONCLUSIONS

In this paper, we describe a coastal economy highly dependent on agriculture and fisheries, to study the interacting external effects of ocean acidification, global warming, and eutrophication on socially optimal environmental policy. The analysis is based on a closed economy and hence, we do not consider the effect of sector emissions on climate change and ocean acidification on the rest of the world. Instead we focus on how national environmental policy can optimally respond to interacting environmental externalities. The structure of the general equilibrium model is consistent with recommendations formulated in recent research on socioeconomic consequences of ocean acidification and appropriate policy responses. Ocean acidification is likely to hit developing coastal economies the hardest as they particularly depend on fishery resources for nutrition and income. In addition, the literature suggests to not study ocean acidification in isolation but in combination with other global and regional environmental stressors. In this paper we combine ocean acidification with global warming and nutrient run-off of fertilizers used in agricultural production, which also contribute to regional acidification. Moreover, we assume that consumers in our economy do not only care about fish and agricultural product consumption, but also care about the quality of the regional natural environment. Our model is the first to take into consideration three externalities in a general equilibrium setting.

We derive optimal rules for taxes on CO_2 emissions and agricultural nutrient run-off and show that they depend on both isolated and interacting damage effects. The optimal carbon tax is the sum of marginal damages from global warming, ocean acidification and their interaction with the effect of nutrient run-off on the environmental quality as well as on production in agriculture and fisheries. It needs to account not only for isolated but also for synergetic damages captured by the interaction term. Thereby eutrophication increases the optimal carbon tax through its interaction with global warming and ocean acidification. The optimal tax on nutrient run-off is the sum of marginal damages from nutrient run-off and its interaction with global warming and ocean acidification on environmental quality as well as on production in the fishery sector. Also in this case synergetic damages, captured by the interaction term, increase the first-best nutrient tax.

In addition, we derive a second-best rule for a tax on agricultural run-off of fertilizers for the realistic case that the carbon tax is set below its Pigouvian level such that CO_2 externalities are not fully internalized. On the one hand we find that the second-best tax on nutrient run-off will be higher than its Pigouvian level to account for the additional marginal damages from carbon emissions on environmental quality and production in both sectors that are not covered by the carbon tax. On the other hand a carbon tax below its Pigouvian level makes carbon intensive fuels, which are a necessary input for production in both sector, relatively cheap. Consequently marginal abatement costs for carbon emissions decrease, which lowers the second-best optimal tax on nutrient run-off compared to its Pigouvian level. Overall we obtain that the former positive effect will be higher than the latter negative effect and thus, the second-best nutrient tax will always be above its Pigouvian level.

Our analysis shows the importance of regulating ocean acidification within a framework of multiple important drivers of environmental change like global warming and eutrophication. Ideally marginal environmental damages from CO_2 emissions should be internalized by a tax on CO_2 emissions that is high enough to not only reflect marginal damages from temperature increases, but also marginal damages from ocean acidification and the interaction of both with regional sources of acidification like nutrient run-off from agriculture. Unfortunately, it is more realistic to expect that CO_2 externalities will not be fully internalized. Moreover, estimating marginal economic damages from ocean acidification is a challenging task that is complicated by the uncertainty about actual and future ecosystem responses. When—for whatever reasons—the tax on CO_2 emissions cannot be equal to its Pigouvian level, regional environmental policy becomes relevant, as has been demonstrated in this paper. A sufficiently high tax on nutrient run-off of fertilizers used in agricultural production can limit not only marginal environmental damages from nutrient run-off but also account for unregulated carbon emissions when the carbon tax is set below the level that internalizes CO_2 externalities. Putting such policies in place will be of particular importance for developing coastal economies that are likely to suffer the most from ocean acidification.

ACKNOWLEDGMENT

We are very grateful to Katrin Rehdanz, Martin Quaas and participants of the World Congress on Natural Resource Modeling 2017 for valuable comments. Martin C. Hänsel acknowledges a PhD Miniproposal grant from the Integrated School of Ocean Sciences in the Excellence Cluster *The Future Ocean* in Kiel. Open Access funding enabled and organized by Projekt DEAL.

AUTHOR CONTRIBUTIONS

Martin C. Hänsel and Jeroen C. J. M. van denBergh jointly conceived the study during a research stay of Martin C. Hänsel at the Institute of Environmental Science and Technology of the Autonomous University of Barcelona. Martin C. Hänsel and Jeroen C. J. M. van denBergh jointly undertook the model design. Martin C. Hänsel performed the literature review, theoretical analysis, and graphical representation of results with substantive input and close feedback from Jeroen C. J. M. van denBergh. The writing of the manuscript was led by Martin C. Hänsel with significant input from Jeroen C. J. M. van denBergh.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no data sets were generated or analysed during the current study.

ORCID

Martin C. Hänsel https://orcid.org/0000-0002-0242-3168
Jeroen C. J. M. van den Bergh https://orcid.org/0000-0003-3415-3083

REFERENCES

Allison, E. H., Perry, A. L., Badjeck, M.-C., NeilAdger, W., Brown, K., Conway, D., Halls, A. S., Pilling, G. M., Reynolds, J. D., Andrew, N. L., & Dulvy, N. K. (2009). Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries*, *10*(2), 173–196.

Ambec, S., & Coria, J. (2013). Prices vs quantities with multiple pollutants. *Journal of Environmental Economics and Management*, *66*(1), 123–140.

Ambec, S., & Coria, J. (2018). Policy spillovers in the regulation of multiple pollutants. *Journal of Environmental Economics and Management*, *87*, 114–134.

Baumgärtner, S., Klein, A. M., Thiel, D., & Winkler, K. (2015). Ramsey discounting of ecosystem services. *Environmental and Resource Economics*, *61*(2), 273–296.

Blanchard, J. L., Jennings, S., Holmes, R., Harle, J., Merino, G., Allen, J. I., Holt, J., Dulvy, N. K., & Barange, M. (2012). Potential consequences of climate change for primary production and fish production in large marine ecosystems. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, *367*(1605), 2979–2989.

Bopp, L., Resplandy, L., Orr, J. C., Doney, S. C., Dunne, J. P., Gehlen, M., Halloran, P., Heinze, C., Ilyina, T., Séférian, R., Tjiputra, J., & Vichi, M. (2013). Multiple stressors of ocean ecosystems in the 21st century: Projections with cmip5 models. *Biogeosciences*, *10*(10), 6225–6245.

Brander, L. M., Rehdanz, K., Tol, R. S. J., & Van Beukering, P. J. H. (2012). The economic impact of ocean acidification on coral reefs. *Climate Change Economics*, *3*(1), 1250002.

Browman, H. I. (2016). Applying organized scepticism to ocean acidification research. *ICES Journal of Marine Science: Journal du Conseil*, *73*(3), 529–536.

Burke, M., & Emerick, K. (2016). Adaptation to climate change: Evidence from US agriculture. *American Economic Journal: Economic Policy*, *8*(3), 106–40.

Cai, W.-J., Hu, X., Huang, W.-J., Murrell, M. C., Lehrter, J. C., Lohrenz, S. E., Chou, W.-C., Zhai, W., Hollibaugh, J. T., Wang, Y., Zhao, P., Guo, X., Gundersen, K., Dai, M., & Gong, G.-C. (2011). Acidification of subsurface coastal waters enhanced by eutrophication. *Nature Geoscience*, *4*, 766–770.

Caplan, A. J., & Silva, E. C. (2005). An efficient mechanism to control correlated externalities: Redistributive transfers and the coexistence of regional and global pollution permit markets. *Journal of Environmental Economics and Management*, *49*(1), 68–82.

Chen, S., Chen, X., & Xu, J. (2016). Impacts of climate change on agriculture: Evidence from China. *Journal of Environmental Economics and Management*, *76*, 105–124.

Cheung, W. W. L., Lam, V. W. Y., Sarmiento, J. L., Kearney, K., Watson, R., Zeller, D., & Pauly, D. (2010). Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology*, *16*(1), 24–35.

Cheung, W. W. L., Watson, R., & Pauly, D. (2013). Signature of ocean warming in global fisheries catch. *Nature*, *497*, 365–368. https://doi.org/10.1038/nature12156

Compton, J. E., Harrison, J. A., Dennis, R. L., Greaver, T. L., Hill, B. H., Jordan, S. J., Walker, H., & Campbell, H. V. (2011). Ecosystem services altered by human changes in the nitrogen cycle: A new perspective for us decision making. *Ecology Letters*, *14*(8), 804–815.

Cooley, S. R., & Doney, S. C. (2009). Anticipating ocean acidification's economic consequences for commercial fisheries. *Environmental Research Letters*, *4*(2), 024007.

Cooley, S. R., Lucey, N., Kite-Powell, H., & Doney, S. C. (2012). Nutrition and income from molluscs today imply vulnerability to ocean acidification tomorrow. *Fish and Fisheries*, *13*(2), 182–215.

Cremer, H., Gahvari, F., & Ladoux, N. (1998). Externalities and optimal taxation. *Journal of Public Economics*, *70*(3), 343–364.

Deschênes, O., & Greenstone, M. (2007). The economic impacts of climate change: Evidence from agricultural output and random fluctuations in weather. *The American Economic Review*, *97*(1), 354–385.

Diaz, R. J., & Rosenberg, R. (2008). Spreading dead zones and consequences for marine ecosystems. *Science*, *321*(5891), 926–929. https://doi.org/10.1126/science.1156401

Doney, S. C., Fabry, V. J., Feely, R. A., & Kleypas, J. A. (2009). Ocean acidification: The other Co_2 problem. *Annual Review of Marine Science*, *1*(1), 169–192.

Drupp, M. A. (2018). Limits to substitution between ecosystem services and manufactured goods and implications for social discounting. *Environmental and Resource Economics*, *69*(1), 135–158.

Endres, A. (1985). Environmental policy with pollutant interaction. In R. Pethig (ed.), *Public Goods and Public Allocation Policy*. Frankfurt/M.

FAO. (2019). Food and agriculture organization of the United Nations: Emissions by sector. http://www.fao.org/faostat/en/#data/EM/visualize

FAO. (2021). Food and agriculture organization of the United Nations: Nutrient nitrogen n (total)—use per area of cropland. http://www.fao.org/faostat/en/#data/EF/visualize

Finger, R. (2012). Nitrogen use and the effects of nitrogen taxation under consideration of production and price risks. *Agricultural Systems*, *107*, 13–20.

Frommel, A. Y., Maneja, R., Lowe, D., Malzahn, A. M., Geffen, A. J., Folkvord, A., Piatkowski, U., Reusch, T. B. H., & Clemmesen, C. (2012). Severe tissue damage in atlantic cod larvae under increasing ocean acidification. *Nature Climate Change*, *2*, 42–46.

Fullerton, D., & Karney, D. H. (2018). Multiple pollutants, co-benefits, and suboptimal environmental policies. *Journal of Environmental Economics and Management*, *87*(1), 52–71. https://doi.org/10.1016/j.jeem.2017.08.003

Gattuso, J.-P. et al. (2014). Ocean acidification: Background and history. In C. Field et al. (eds.), *Ocean Acidification* (pp. 129–131). Cambridge University Press.

Gattuso, J.-P., Magnan, A., Billé, R., Cheung, W. W. L., Howes, E. L., Joos, F., Allemand, D., Bopp, L., Cooley, S. R., Eakin, C. M., Hoegh-Guldberg, O., Kelly, R. P., Pörtner, H.-O., Rogers, A. D., Baxter, J. M., Laffoley, D., Osborn, D., Rankovic, A., Rochette, J., Sumaila, U. R., Treyer, S., & Turley, C. (2015). Contrasting futures for ocean and society from different anthropogenic Co_2 emissions scenarios. *Science*, *349*(6243).

Goldberg, J. (2016). Kwacha gonna do? experimental evidence about labor supply in rural Malawi. *American Economic Journal: Applied Economics*, *8*(1), 129–149.

Hänsel, M. C., Schmidt, J. O., Stiasny, M. H., Stöven, M. T., Voss, R., & Quaas, M. F. (2020). Ocean warming and acidification may drag down the commercial arctic cod fishery by 2100. *PLOS One*, *15*(4), 1–14.

Hilmi, N., Allemand, D., Dupont, S., Safa, A., Haraldsson, G., Nunes, P. A. L. D., Moore, C., Hattam, C., Reynaud, S., Hall-Spencer, J. M., Fine, M., Turley, C., Jeffree, R., Orr, J., Munday, P. L., & Cooley, S. R.(2012). Towards improved socio-economic assessments of ocean acidification's impacts. *Marine Biology*, *160*(8), 1773–1787.

Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S., Greenfield, P., Gomez, E., Harvell, C. D., Sale, P. F., Edwards, A. J., Caldeira, K., Knowlton, N., Eakin, C. M., Iglesias-Prieto, R., Muthiga, N., Bradbury, R. H., Dubi, A., & Hatziolos, M. E. (2007). Coral reefs under rapid climate change and ocean acidification. *Science*, *318*(5857), 1737–1742.

Hoel, M. (2012). *Second-best climate policy*. Memorandum. Department of Economics, University of Oslo, Oslo.

Hoel, M., & Sterner, T. (2027). Discounting and relative prices. *Climatic Change*, *84*(3), 265–280.

IPCC. (2013). *Climate change 2013: The physical science basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Kelly, R. P., Foley, M. M., Fisher, W. S., Feely, R. A., Halpern, B. S., Waldbusser, G. G., & Caldwell, M. R. (2011). Mitigating local causes of ocean acidification with existing laws. *Science*, *332*(6033), 1036–1037.

Kroeker, K. J., Kordas, R. L., Crim, R., Hendriks, I. E., Ramajo, L., Singh, G. S., Duarte, C. M., & Gattuso, J.-P. (2013). Impacts of ocean acidification on marine organisms: Quantifying sensitivities and interaction with warming. *Global Change Biology*, *19*(6), 1884–1896.

Kroeker, K. J., Kordas, R. L., Crim, R. N., & Singh, G. G. (2010). Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. *Ecology Letters*, *13*(11), 1419–1434.

Krutilla, K. (1991). Environmental regulation in an open economy. *Journal of Environmental Economics and Management*, *20*(2), 127–142. https://doi.org/10.1016/0095-0696(91)90046-L

Legras, S. (2011). Incomplete model specification in a multi-pollutants setting: The case of climate change and acidification. *Resource and Energy Economics*, *33*(3), 527–543.

Markusen, J. R. (1975). International externalities and optimal tax structures. *Journal of International Economics*, *5*(1), 15–29.

Mendelsohn, R., Nordhaus, W. D., & Shaw, D. (1994). The impact of global warming on agriculture: A ricardian analysis. *The American Economic Review*, *84*(4), 753–771.

Meyer, J., & Riebesell, U. (2015). Reviews and syntheses: Responses of coccolithophores to ocean acidification: A meta-analysis. *Biogeosciences*, *12*(6), 1671–1682.

Morton, J. F. (2007). The impact of climate change on smallholder and subsistence agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(50), 19680–19685.

Moslener, U., & Requate, T. (2007). Optimal abatement in dynamic multi-pollutant problems when pollutants can be complements or substitutes. *Journal of Economic Dynamics and Control*, *31*(7), 2293–2316.

Narita, D., Rehdanz, K., & Tol, R. S. J. (2012). Economic costs of ocean acidification: A look into the impacts on global shellfish production. *Climatic Change*, *113*(3), 1049–1063.

NOAA. (2017). *NOAA global climate change report—February 2017*. https://www.ncdc.noaa.gov/sotc/global/201702

Pearce, D., & Koundouri, P. (2003). *Fertilizer and pesticide taxes for controlling non-point agricultural pollution*. Report issued by: The World Bank Group.

Rau, G. H., McLeod, E. L., & Hoegh-Guldberg, O. (2012). The need for new ocean conservation strategies in a high-carbon dioxide world. *Nature Climate Change*, *2*, 720–274.

Ren, X., Fullerton, D., & Braden, J. B. (2011). Optimal taxation of externalities interacting through markets: A theoretical general equilibrium analysis. *Resource and Energy Economics*, *33*(3), 496–514.

Repetto, R. (1987). The policy implications of non-convex environmental damages: A smog control case study. *Journal of Environmental Economics and Management*, *14*(1), 13–29.

Riebesell, U., & Gattuso, J.-P. (2015). Lessons learned from ocean acidification research. *Climate Change*, *5*, 12–14.

Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sorlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., & Foley, J. A. (2009). A safe operating space for humanity. *Nature*, *461*(7263), 472–475.

Rodrigues, L. C., Bergh, J. C. J. M., Loureiro, M. L., Nunes, P. A. L. D., & Rossi, S. (2015). The cost of mediterranean sea warming and acidification: A choice experiment among scuba divers at medes islands, spain. *Environmental and Resource Economics*, *63*(2), 289–311.

Rougoor, C. W., Zeijts, H. V., Hofreither, M. F., & Bäckman, S. (2001). Experiences with fertilizer taxes in europe. *Journal of Environmental Planning and Management*, *44*(6), 877–887.

Russell, C. S., & Shogren, J. F. (1993). *Theory, Modeling and Experience in the Management of Nonpoint-Source Pollution*. Boston, MA: Springer.

Schlenker, W., Hanemann, M., & Fisher, A. C. (2006). The impact of global warming on u.s. agriculture: An econometric analysis of optimal growing conditions. *The Review of Economics and Statistics*, *88*(1), 113–125.

Schlenker, W., & Roberts, M. J. (2009). Nonlinear temperature effects indicate severe damages to u.s. crop yields under climate change.*Proceedings of the National Academy of Sciences of the United States of America*, *106*(37), 15594–15598.

Stern, N. (2007). *Stern Review on the Economics of Climate Change*. Government Economics Service.

Stiasny, M. H., Mittermayer, F. H., Sswat, M., Voss, R., Jutfelt, F., Chierici, M., Puvanendran, V., Mortensen, A., Reusch, T. B. H., & Clemmesen, C. (2016). Ocean acidification effects on atlantic cod larval survival and recruitment to the fished population. *PLOS One*, *11*(8), e0155448.

Strong, A. L., Kroeker, K. J., Teneva, L. T., Mease, L. A., & Kelly, R. P. (2014). Ocean acidification 2.0: Managing our changing coastal ocean chemistry. *BioScience*.

Talmage, S. C., & Gobler, C. J. (2010). Effects of past, present, and future ocean carbon dioxide concentrations on the growth and survival of larval shellfish. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(40), 17246–17251.

Turley, C., & Gattuso, J.-P. (2012). Future biological and ecosystem impacts of ocean acidification and their socioeconomic-policy implications. *Current Opinion in Environmental Sustainability*, *4*(3), 278–286.

Voss, R., Quaas, M. F., Schmidt, J. O., & Kapaun, U. (2015). Ocean acidification may aggravate social-ecological trade-offs in coastal fisheries. *PLOS One*, *10*(3), 1–8.

Voss, R., Quaas, M. F., Stiasny, M. H., Hänsel, M., Pinto, G. A. S. J., Lehmann, A., Reusch, T. B., & Schmidt, J. O. (2019). Ecological-economic sustainability of the baltic cod fisheries under ocean warming and acidification. *Journal of Environmental Management*, *238*, 110–118.

Waldbusser, G. G., Hales, B., & Haley, B. A. (2016). Calcium carbonate saturation state: On myths and this or that stories. *ICES Journal of Marine Science: Journal du Conseil*, *73*(3), 563–568.

Welch, J. R., Vincent, J. R., Auffhammer, M., Moya, P. F., Dobermann, A., & Dawe, D. (2010). Rice yields in tropical/subtropical asia exhibit large but opposing sensitivities to minimum and maximum temperatures. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(33), 14562–14567.

Xepapadeas, A. (2011). The economics of non-point-source pollution. *Annual Review of Resource Economics*, *3*(1), 355–373.

How to cite this article: Hänsel, M. C., & van den Bergh, J. C. J. M. (2021). Taxing interacting externalities of ocean acidification, global warming, and eutrophication. *Natural Resource Modeling*. 34, e12317. https://doi.org/10.1111/nrm.12317