Environ Resource Econ (2012) 52:49–64
DOI 10.1007/s10640-011-9519-1

Adaptation and Mitigation in Global Pollution Problems: Economic Impacts of Productivity, Sensitivity, and Adaptive Capacity

Udo Ebert · Heinz Welsch

Accepted: 25 September 2011 / Published online: 25 October 2011

Abstract This paper studies the influence of productivity, pollution sensitivity, and adaptive capacity on optimal mitigation and adaptation in a two-country global pollution model. We investigate the effects of changes of these parameters on the allocation of emissions, adaptation expenditures, and welfare. In our analysis we distinguish between cooperative and non-cooperative behavior. Our findings imply that unilateral improvements in productivity and adaptive capacity have strategic significance and do not necessarily lead to mutual welfare improvements. They raise the emissions not only in the country where the technological improvement takes place, but also globally. An improvement in global welfare is guaranteed only under cooperative behavior with respect to emission and adaptation choices.

Keywords Global pollution · Adaptation · Mitigation · Cooperative behavior · Nash equilibrium · Comparative Statics

JEL Classification Q58 · Q54

1 Introduction

While the economic analysis of global pollution has mostly focused on emission reduction (mitigation), some recent literature has started to address the issue of how countries can protect themselves against the adverse impacts of global pollution by means of adaptation. The new focus on adaptation may be viewed as resulting from an increased awareness that, due to free rider incentives and a lack of enforcement institutions, effective international agreements on the reduction of global emissions are difficult to achieve. In contrast to mitigation of global pollution, adaptation does not require an international consensus.

U. Ebert (✉) · H. Welsch
Department of Economics, University of Oldenburg, 26111 Oldenburg, Germany
e-mail: ebert@uni-oldenburg.de

H. Welsch
e-mail: welsch@uni-oldenburg.de

Though adaptation can be implemented on a national basis, decisions on optimal adaptation must take the level of emissions into account. Since mitigation and adaptation are substitutes with respect to damage prevention (Ingham et al. 2007), the issue arises as to the optimal mix between the two (Kane and Shogren 2000; Lecoq and Shalizi 2007; Tulkens and van Steenberghe 2009). The optimal mix will be different for different patterns of behavior (cooperative versus non-cooperative). In addition, it will depend on the countries' costs of mitigation, their adaptive capacity as well as on their sensitivity to pollution.

The main purpose of this paper is to study the influence of these latter parameters on 'optimal' mitigation and adaptation in alternative behavioral scenarios, that is, by considering the global welfare optimum (fully cooperative behavior) and the Nash equilibrium (non-cooperative behavior). Specifically, we investigate how a country's mitigation costs, its adaptive capacity, and its sensitivity to pollution affect the allocation of emissions, adaptation expenditures, and welfare. In our analysis we capture the marginal costs of mitigation (emission reduction) by the marginal benefits from emissions, that is, we identify costs with benefits foregone. A major determinant of those benefits is the productivity of emissions in the production process. Moreover, we derive and use a reduced-form (optimally adapted) welfare function. This methodological device greatly facilitates our analysis. To keep matters tractable, we confine ourselves to the two-country case.

Concerning the parameters that we study, a country's sensitivity to pollution can largely be considered as a 'natural endowment', related to the country's geography. In contrast to that, the economic benefits from emissions can to some extent be influenced by economic choices, e.g. by investing in higher carbon efficiency. Similarly, the effectiveness of adaptation measures may be increased, e.g. by improvements in irrigation technology. In fact, in dealing with global pollution, many countries have started taking measures to increase the productivity of emissions (or of the inputs which cause them) and the effectiveness of adaptation.[1]

According to our analysis, such technological changes will affect the outcomes of the global pollution game. For instance, in the non-cooperative case, raising the benefits from emissions or the adaptation capabilities in one country will under standard conditions induce the other country to reduce its emissions and will imply a welfare loss in that country. Efforts to attain technological improvements in mitigation and adaptation technology thus have strategic significance. In the case of cooperative behavior, improvements in one country's adaptive capacity may be mutually beneficial, but improvements in the benefits from emissions still have negative effects on the other country's welfare. In no case are such technological improvements in one country unambiguously of mutual advantage.

In addition to their effects on welfare, unilateral improvements in productivity and adaptive capacity unambiguously raise the emissions not only in the country where the technological improvement takes place, but globally. In promoting efforts to attain the technological improvements studied, decision makers should be aware of these effects.

An early study of the interdependence of abatement (mitigation) and self protection (adaptation) is Shibata and Winrich (1983). Kane and Shogren (2000) study the influence of uncertainty on the mitigation-adaptation choice. While Ingham et al. (2007) and Lecoq and Shalizi (2007) emphasize the substitutability of mitigation and adaptation, Tol (2005) discusses trade-offs in substance and methods between the two. Zehaie (2009) investigates the

[1] An example of the former kind of measures is the European Union's "EU Climate and Energy Package" which stipulates a "reduction in primary energy use … to be achieved by *improving energy efficiency*" (see http://ec.europa.eu/envi\discretionary-ron\discretionary-ment/cli\discretionary-mat/cli\discretionary-mate_action.htm, emphasis added).

possible strategic role of adaptation measures (but not technology changes) under various assumptions on the timing of mitigation and adaptation decisions.

To our knowledge, none of the previous literature has studied the impacts of changes in a country's economic benefits from emissions, its adaptive capacity and its sensitivity to pollution in a mitigation-adaptation framework. Even in more simple (traditional) models which disregard adaptation, the effects of changes in the benefits from emissions or differences in the sensitivity to pollution do not seem to have been investigated. Our analysis shows that those effects are—qualitatively—the same no matter whether adaptation possibilities are admitted or not.

The paper is organized as follows. Section 2 develops the model and presents a basic proposition. Section 3 derives and discusses our results. Section 4 concludes.

2 The Model and a Basic Proposition[2]

2.1 The General Approach

We start by setting up our model of global pollution and adaptation to (or self-protection against) pollution. Since we are not interested in (dynamic) issues of learning and uncertainty (as are, e.g., Ingham et al. 2007), we proceed in a static framework without uncertainty (as do Hoel 1991; Welsch 1993; Barrett 2008). Moreover, following much of the literature (Hoel 1991; Zehaie 2009), we employ a two-country framework, i.e., we assume that the world consists of two countries.

As stated in the introduction, we will consider cooperative and non-cooperative behavior of the two countries. In the case of non-cooperative behavior the question arises as to the sequence of moves with respect to emissions and adaptation. Three possibilities are conceivable: (a) emissions before adaptation, (b) emissions simultaneously with adaptation, (c) emissions after adaptation.

We deem case (c) to be not very relevant: Since we shall assume below that emissions are essential (indispensable) to economic activity, it is not possible to postpone them after adaptation measures have been taken. With respect to cases (a) and (b), Zehaie (2009) has shown that they are equivalent. Nevertheless, a clarification is necessary with respect to one specific aspect of our methodological approach, namely the use of reduced-form (optimally adapted) welfare functions for the two countries. The optimally adapted welfare function will be derived by determining, in a first step, each country's optimal adaptation as a function of the emissions of both countries. In the context of case (a)—emissions before adaptation—this can be viewed as the first step in solving the two-stage game *backwards* in order to obtain a subgame-perfect Nash equilibrium. In the context of case (b)—emissions simultaneously with adaptation—the optimally adapted welfare function is just a useful technique to reduce the problem from four to two dimensions.

Since the approach of using the optimally adapted welfare function is consistent with both cases (a) and (b), and since these two cases are strategically equivalent, we will assume that emissions and adaptation take place simultaneously and proceed in a static framework.

Another aspect to be addressed in advance is our way of modeling adaptation. Adaptation involves a large variety of physical measures, such as constructing dikes, moving buildings, shifting crops etc. There exists no common physical metric for these diverse measures (Lecoq and Shalizi 2007; Barrett 2008). We will therefore include adaptation *expenditures* as

[2] Parts of this section are based on Ebert and Welsch (2011).

an argument in the damage function and assume that the damage function implicitly reflects an optimal mix of adaptation options.

2.2 Assumptions

A country's emissions, E, yield economic benefit equal to the sum of consumer and producer surplus from a produced good Y. Emissions serve as an input in the production of this good, $Y = Y(E)$. Benefits can be written as $\tilde{B}(Y(E))$. We set $B(E) := \tilde{B}(Y(E))$. Since some models in the literature are formulated in terms of emission reductions rather than emissions it should be noted that the marginal economic benefits from emissions are identical to the marginal costs (benefits forgone) of emission reduction (mitigation). Furthermore we assume that emissions are an essential input. This implies that production (and consumption) without emitting pollutants is impossible. Since we assume that benefit is measured in monetary units, B is always nonnegative.

A country's benefit function is assumed to be twice continuously differentiable and to have the usual properties of strict monotonicity and strict concavity:

$$B' > 0, \quad B'' < 0 \tag{1}$$

Let E^* denote the other country's emissions and assume that global emissions, $E + E^*$, imply (monetized) damage $D(E + E^*, A)$ in the country considered. In this formulation A denotes expenditures on adaptation. The postulated relationship between adaptation expenditures and damage is based on assuming an optimal mix of physical adaptation options, that is, adaptation expenditures A are allocated to available adaptation options in such a way that the reduction in damage at a given emission level is maximized.

The damage function is also twice continuously differentiable and has the following properties:

$$D_E > 0, \quad D_A < 0 \tag{2}$$

$$D_{EE} > 0, \quad D_{AA} > 0 \tag{3}$$

$$D_{EA} = D_{AE} < 0 \tag{4}$$

where D_A, D_{EE}, D_{AE} etc. denote partial derivatives.

Condition (2) says that (monetized) damage increases in global emissions and decreases in adaptation expenditures. Condition (3) means that there is increasing marginal damage from emissions and decreasing effectiveness of adaptation. Condition (4) says that increasing adaptation expenditures reduces the marginal damage from emissions, while increasing emissions increases the marginal damage reduction from adaptation.[3]

The country's welfare is defined by

$$W(E, E^*, A) = B(E) - D(E + E^*, A) - A.$$

Welfare is assumed to be strictly concave in (E, A), which is equivalent to $B'' - D_{EE} < 0, \quad D_{AA} > 0$ (implied by (1) and (3)), and

$$D_{EE} - D_{EA}^2 / D_{AA} - B'' > 0. \tag{5}$$

[3] Assumption (4) is consistent with Ingham et al. (2005) and Tulkens and van Steenberghe (2009). For a substantive argument see Lecoq and Shalizi (2007).

2.3 Welfare Maximization by One Country

As noted above it will prove useful to formulate the country's welfare maximization as a two-stage problem. In the first stage, welfare is maximized with respect to adaptation expenditures:

$$\max_A \; W(E, E^*, A).$$

The first-order condition

$$\frac{\partial W}{\partial A} = -D_A(E + E^*, A) - 1 = 0$$

says that adaptation should be pushed to the point where the damage reduction from a marginal increase in adaptation expenditures is unity. The condition yields optimal adaptation expenditures as a function of global emissions, $A = A(E + E^*)$. Given a (generally) nonseparable damage function D, the global level of emissions thus determines a country's optimal adaptation effort. From the implicit function theorem we obtain the properties

$$\frac{\partial A}{\partial E} = \frac{\partial A}{\partial E^*} = -\frac{D_{AE}}{D_{AA}} > 0.$$

Optimal adaptation expenditures are thus an increasing function of each country's emissions.

Replacing A in $W(E, E^*, A)$ with $A = A(E + E^*)$ gives the reduced-form (optimally adapted) welfare function

$$\hat{W}(E, E^*) := W(E, E^*, A(E + E^*)),$$

which is strictly concave in E and concave in (E, E^*).

In the second stage, welfare maximizing emissions are determined such as to

$$\max_E \; \hat{W}(E, E^*).$$

The first-order condition

$$\frac{\partial \hat{W}}{\partial E} = B'(E) - D_E(E + E^*, A(E + E^*)) = 0$$

says that emissions should be pushed to the point where marginal benefit equals marginal damage, taking optimal adaptation into account. The condition yields the *optimal emission response function* $E = R^E(E^*)$ whose derivative is given by

$$\frac{dE}{dE^*} = R^{E'}(E^*) = \frac{\upsilon}{B'' - \upsilon}, \tag{6}$$

where $\upsilon := D_{EE} - D_{EA}^2/D_{AA}$ is a measure of a country's vulnerability (see below).

Replacing E in $A = A(E + E^*)$ with $E = R^E(E^*)$ gives an *optimal adaptation response function* $A = R^A(E^*)$ with derivative

$$\frac{dA}{dE^*} = R^{A'}(E^*) = \frac{dA}{dE}(R^{E'}(E^*) + 1).$$

The properties of the optimal emission and adaptation response function are stated in

Proposition 1 *Under assumptions* (1)–(5)*, the following holds:*

- *If* $\upsilon \geq 0$ *(case 1), then* $-1 < R^{E'}(E^*) \leq 0$.
- *If* $\upsilon < 0$ *(case 2), then* $R^{E'}(E^*) > 0$.

Moreover,

$$R^{A'}\left(E^*\right) > 0.$$

Thus, the slope of the optimal emission response function can take values from the interval $(-1, 0]$ or can be positive, depending on the sign of the expression υ. The optimal adaptation response function is upward sloping in both case 1 and case 2, that is, a country responds to the other country raising its emissions by increasing its adaptation effort.

2.4 Discussion

As seen from (6) the crucial term for the slope of the optimal emission response function is the expression $D_{EE} - D_{EA}^2/D_{AA}$. A large value for D_{EE} (steep marginal damage function) indicates high sensitivity to global pollution. A large value for D_{EA}^2/D_{AA} indicates high adaptation capacity: The effectiveness of adaptation in reducing marginal damage, $|D_{EA}|$, is large, and/or the extent by which effectiveness of adaptation diminishes, D_{AA}, is small. In the terminology of IPCC (2007), high sensitivity to pollution combined with low adaptation capacity is referred to as high vulnerability. In this sense, a large (small) value of $D_{EE} - D_{EA}^2/D_{AA}$ indicates high (low) vulnerability of the country considered.

Proposition 1 thus entails that the optimal emission response function is downward sloping in the case of high vulnerability. In the terminology of Bulow et al. (1985), this means that emissions are strategic substitutes. Downward sloping optimal emission response functions are a standard finding in models of global pollution which disregard adaptation possibilities (Hoel 1991; Welsch 1993; Finus and Maus 2008, among many others). In the case of sufficiently large adaptation capacity, however, the optimal emission response function will be upward sloping, that is, emissions become strategic complements.

For the second country, similar relationships hold. The second country's benefit, damage, welfare and response functions are also assumed to possess the properties discussed above. These functions will be indicated by an asterisk.

3 Results

3.1 Solutions of the Model

Up to now we have focused on one country. In the following we will consider the interaction of the two countries. We differentiate between cooperative and non-cooperative patterns of behavior by considering the global welfare optimum and the Nash equilibrium. In this analysis the reduced-form welfare function introduced above will prove to be a helpful tool since it reduces the dimension of the problem.

At first we examine the global welfare optimum $\left(E_G, E_G^*\right)$ for the two countries. The objective is given by the aggregate welfare function of both countries. The resulting allocation represents a reference allocation for the normative assessment of the Nash equilibrium. Using the reduced-form welfare functions we obtain global (aggregate) welfare as

$$\hat{W}\left(E, E^*\right) + \hat{W}^*\left(E^*, E\right).$$

Given the properties of the individual welfare functions this global welfare function is strictly concave in (E, E^*). Therefore a unique solution of the corresponding maximization problem exists which is characterized by[4]

$$B'(E_G) = B^{*\prime}\left(E_G^*\right) = D_E\left(E_G + E_G^*, A\left(E_G + E_G^*\right)\right) + D_E^*\left(E_G^* + E_G, A^*\left(E_G^* + E_G\right)\right) \tag{7}$$

for the global optimum $\left(E_G, E_G^*\right)$.

This means that both countries' marginal benefits have to coincide and have to be equal to the sum of marginal damages. The second part of the condition reflects the fact that emissions damage both countries simultaneously. Therefore the right hand part of equation (7) represents the Samuelson rule.

In a second step we investigate the Nash equilibrium $\left(E_N, E_N^*\right)$. Each country maximizes its welfare given the other country's behavior. Then the first-order conditions derived in Sect. 2.3 hold. We obtain

$$B'(E_N) = D_E\left(E_N + E_N^*, A\left(E_N + E_N^*\right)\right)$$

and

$$B^{*\prime}\left(E_N^*\right) = D_E^*\left(E_N^* + E_N, A^*\left(E_N^* + E_N\right)\right).$$

In this case the marginal benefit of each country's emissions is equal to the marginal damage in that country. The other country's damages are neglected. This solution is inefficient.

An equilibrium always exists (because of the continuity and concavity of the welfare functions). Furthermore, the equilibrium is unique if $\left(B'' - \upsilon\right)\left(B^{*\prime\prime} - \upsilon^*\right) - (\upsilon + \upsilon^*)/4 > 0$ (cf. Rosen 1965).

3.2 Comparative Static Analysis

In this subsection we study the effect of changes in a country's benefit from emission, its adaptive capacity, and its sensitivity to global pollution. For a comparative static analysis of these effects we introduce some (exogenous) parameters which can be varied. Therefore we now assume that for one country, which we henceforth call the home country, the benefit function is given by $bB(E)$ and the damage function by $D(e(E + E^*), aA)$, where $a, b, e > 0$ represent parameters. An increase in b means that the home country's emissions are more beneficial. An increase in e means that the country is more sensitive to pollution, whereas an increase in a indicates higher effectiveness of adaptation. It should be clear that—as a consequence—the adaptation function A and the vulnerability υ also depend on these parameters. There is no change for the other country, which we will call the foreign country. Without loss of generality we can assume that $a = b = e = 1$ in the initial situation.

We again distinguish between global welfare maximization and the Nash equilibrium. In both scenarios we start from the respective first-order conditions, introduce their total differentials, and rearrange the terms generated. The details are discussed in the Appendix.

We start by considering global welfare maximization. Here we always suppose that $\upsilon + \upsilon^* \geq 0$, which is a sufficient condition for a comparative statics analysis to be feasible.[5] We first focus on the case that both $\upsilon \geq 0$ and $\upsilon^* \geq 0$. The results of the comparative statics are collected in Table 1. Given that the aim is the maximization of global welfare, it is intuitive

[4] Since the partial derivatives D_E and D_{E^*} and, respectively, D_E^* and $D_{E^*}^*$ are identical we always use D_E and D_E^* in order to keep the notation simple.

[5] It allows us to invert the symmetric square matrix of the second-order partial derivatives, see the Appendix.

Table 1 Global welfare maximization

	$db > 0$	$de > 0$	$da > 0$
dE	+	−	+
dE^*	−	−	+
$dE + dE^*$	+	−	+
dA	+	?	?
dA^*	+	−	+
$d\hat{W}$	+	?	?
$d\hat{W}^*$	−	?	?
$d\hat{W} + d\hat{W}^*$	+	−	+

Assumption: $\upsilon \geq 0$ and $\upsilon^* \geq 0$. It is always assumed that exactly one (!) parameter is changed

that an increase in b and a will improve the overall situation, whereas an increase in e will deteriorate it.

The results for $db > 0$ are consistent with this idea. As the home country's emissions become more beneficial its emissions are increased whereas the foreign country's emissions have to be reduced, but the effect on the global emissions is still positive. Since global emissions increase, adaptation in both countries rises. Then the home country faces an increase and the foreign country a decrease in welfare and we get an improvement in total welfare.

If e is increased pollution becomes more damaging in the home country. Therefore the optimal emissions in both countries are reduced. The implications for adaptation in the home country are not clear because there are two opposing effects: adaptation is reduced because of the decrease in emissions, but increased due to the increase in the effectiveness of adaptation. For the adaptation in the foreign country the latter impact is missing. Thus adaptation is reduced. Global welfare decreases, but the welfare implications for the individual countries are ambiguous.

An improvement in adaptive capacity of the home country ($da > 0$) leads to an improvement in global welfare. It allows both countries to raise their emissions. The impact on the home country's adaptation is again ambiguous since it is pushed by the increase in emissions and dampened by the improvement $da > 0$. While global welfare rises, the effects on each country's welfare are ambiguous. In principle we obtain for $da > 0$ the converse result to the case $de > 0$.

If the vulnerability of the home country is sufficiently low, i.e., $\upsilon < 0$, then several effects become ambiguous.

For the Nash equilibrium some results are different. While for the maximization of global welfare both countries have a common objective and every change in one of the parameters concerns both countries in a similar way, now any improvement or deterioration is at first related to the home country and then indirectly to the foreign country via this country's reaction. The results are assembled in Table 2 again for the standard technologies $\upsilon \geq 0$ and $\upsilon^* \geq 0$.

An increase in the home country's benefits ($db > 0$) has largely similar (qualitative) implications as before. Especially, emissions and welfare rise in the home country and decrease in the foreign country. But now the foreign country is affected more negatively than in the cooperative scenario, and the sign of global welfare is therefore ambiguous. Similarly, now the rise in the home country's sensitivity ($de > 0$) and the corresponding decrease in its emissions are unambiguously advantageous for the foreign country. It raises its emissions, but the global impact on welfare is indefinite.

Table 2 Nash equilibrium

	$db > 0$	$de > 0$	$da > 0$
dE	+	−	+
dE^*	−	+	−
$dE + dE^*$	+	−	+
dA	+	?	?
dA^*	+	−	+
$d\hat{W}$	+	−	+
$d\hat{W}^*$	−	+	−
$d\hat{W} + d\hat{W}^*$	?	?	?

Assumption: $\upsilon \geq 0$ and $\upsilon^* \geq 0$. It is always assumed that exactly one (!) parameter is changed.

The improvement in the home country's adaptation possibilities $da > 0$ leads to an increase in its emissions, but to a decrease in the emissions of the foreign country since now the latter reacts. Again all effects of $da > 0$ are mirror images of those implied by $de > 0$. Especially, the home country's welfare increases and the foreign country's welfare decreases.

Finally, we consider the variant that the home country possesses a nonstandard technology ($\upsilon < 0$). Here we have to assume that $bB'' - \upsilon < 0$. In this situation the implications for emissions of an increase in e are ambiguous, since in equilibrium the home country might reduce or increase its emissions.

It should be mentioned that the qualitative effects of $db > 0$ and $de > 0$ on the variables E, E^*, $E + E^*$, $\hat{W}$, $\hat{W}^*$, $\hat{W} + \hat{W}^*$ are identical to those in a simple model in which adaptation is absent (then $\upsilon \equiv D_{EE} > 0$). This result holds for both welfare maximization and the Nash equilibrium.

Now we want to illustrate the comparative statics of the Nash equilibrium by means of two figures. We first concentrate on a productivity increase $db > 0$. Other parameter changes will be considered later.

We start with the case $\upsilon \geq 0$ and $\upsilon^* \geq 0$, that is, emissions are strategic substitutes for both countries. Figure 1 illustrates this situation. Proposition 1 demonstrates that in this case the slope of each reaction curve must be nonpositive and greater than -1, measured with respect to the relevant axis. Therefore, each reaction curve must be downward sloping and flatter than the lines representing equal global emissions, i.e. $E + E^* = const$. An investigation of the first-order condition for the home country shows that the reaction curve is shifted to the right by $db > 0$. The magnitude of the shift will in general depend on E^*. Without loss of generality we have used linear reaction curves and a uniform (parallel) shift of the home country's curve for illustration. It is obvious that—given the slopes of the reaction curves—the home country will increase and the foreign country will decrease its emissions. Global emissions must increase, too.

Things are different if we have $\upsilon < 0$ and $\upsilon^* < 0$, that is, if emissions are strategic complements for both countries. This situation is presented by Fig. 2 under the condition that $bB'' - \upsilon < 0$. Since the direction of the shift of the home country's reaction curve is independent of υ, the curve is again shifted to the right by $db > 0$. Given its slope and the foreign country's reaction curve, both countries will increase their emissions.

We now consider variations of the other parameters. Qualitatively we obtain the same results for $da > 0$ as for $db > 0$ (the home country's reaction curve is shifted to the right in both Figs. 1 and 2). For $de > 0$, $\upsilon \geq 0$ and $\upsilon^* \geq 0$ the outcome presented in Fig. 1 is reversed (the home country's reaction curve is shifted to the left). If $\upsilon < 0$, the impact of $de > 0$ on the reaction curve is ambiguous.

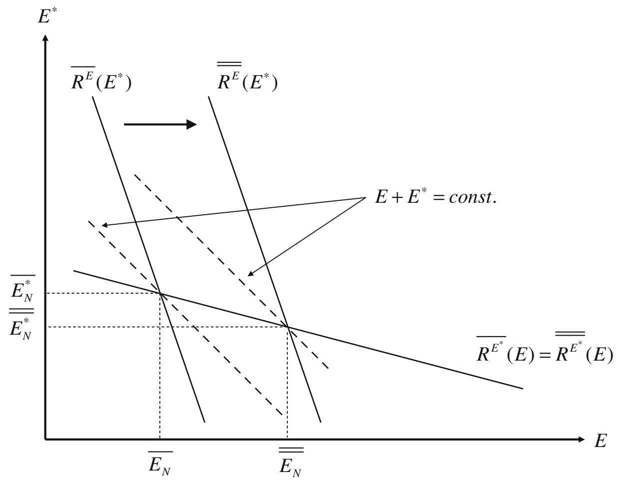

Fig. 1 Change of the Nash-equilibrium for $db > 0,\ da = 0,\ de = 0$, if $\upsilon > 0$ and $\upsilon^* > 0$. $\bar{E}_N$ etc. denote the old, $\bar{\bar{E}}_N$ etc. the new situation

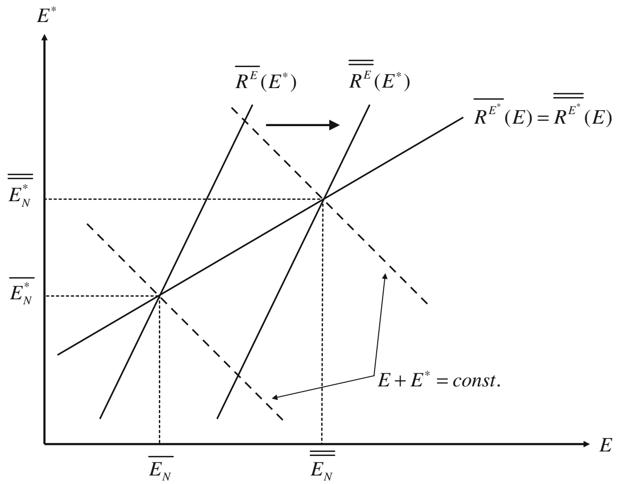

Fig. 2 Change of the Nash-equilibrium for $db > 0, da = 0, de = 0$*, if* $\upsilon < 0$ and $\upsilon^* < 0$. $\overline{E}_N$ etc. denote the old, $\overline{\overline{E}}_N$ etc. the new situation

Finally, we consider the mixed cases: emissions are substitutes for one and complements for the other country. Then it turns out that the situation in the foreign country is decisive: If here emissions are substitutes, the outcome is analogous to the situation depicted in Fig. 1; only the slopes of the home country's reaction curves are different. If emissions in the foreign country are complements, we obtain the outcome illustrated in Fig. 2; again only the slopes of the home country's reaction curves are different.

Overall, greater productivity of emissions or greater adaptive capacity in the home country always lead to greater emissions in the home country and globally, independent of whether emissions are strategic substitutes or complements in the home country and abroad.

3.3 Discussion

Focusing on the detailed results for the standard case of strategic substitutes in both countries, as presented in Tables 1 and 2, a number of insights can be gained.

When considering improvements in a country's benefits from emissions (viz. productivity improvements), we see that their effects on emissions and welfare in the 'home' country are opposite in sign to those in the foreign country. While emissions and welfare increase in the home country, they decrease in the foreign country. This is true not only under non-cooperative behavior, but also under full cooperation. Improvements in adaptive capacity also have opposite home country and foreign country effects on emissions and welfare in the non-cooperative scenario. Under cooperative behavior they lead to increasing emissions not only in the home country, but also in the foreign country. Under both behavioral scenarios, however, both types of technological improvement imply an increase in *global* emissions.

The emission enhancing effect of productivity improvements is intuitive, since such improvements imply an increase in the benefits foregone when emissions are *reduced*, that is, an increase in marginal mitigation costs. Higher marginal mitigation costs clearly imply higher emissions. The emission enhancing effect of improvements in adaptive capacity is intuitive, since these improvements reduce the marginal damage from emissions.

As regards welfare, the two types of technological improvement yield an increase in global welfare under cooperative but not necessarily under non-cooperative behavior. In the latter scenario the home country disregards the negative effect of its 'technologically induced' increase in emissions on the foreign country. Even though the latter reacts by reducing its emissions and increasing its adaptation effort, there is a welfare loss in the foreign country. This welfare loss can be so strong that global welfare decreases.

As far as the effects of improved adaptation capacity are of a definite sign, they are opposite to the effects of a greater sensitivity to pollution. Improvements in adaptive capacity are thus qualitatively equivalent to lower pollution sensitivity.

From a policy point of view, it is remarkable that improvements in productivity and adaptive capacity lead to higher emissions. Though intuitive, it is questionable whether policy makers are aware of this effect when promoting such improvements.

In a welfare sense, rising emissions need not be detrimental per se. As seen, an improvement in productivity leads to an increase in the welfare of the home country. An improvement in adaptive capacity leads to such an improvement in the Nash equilibrium, whereas the effect under global welfare maximization is ambiguous. An increase in *global* welfare, however, is guaranteed only under global welfare maximization, not in the Nash equilibrium. Moreover, in none of the behavioral scenarios are such technological improvements in one country unambiguously welfare enhancing for the other country. Rather, they are clearly detrimental, except for improvements in adaptive capacity under global welfare maximization (in which case the effect is ambiguous).

4 Conclusions

This paper has studied the influence of productivity, pollution sensitivity, and adaptive capacity on optimal mitigation and adaptation in a two-country global pollution framework. We investigated the effects of changes of these parameters in one country on the allocation of emissions, adaptation expenditures, and welfare. As an important methodological device we derived and used a reduced-form (optimally adapted) welfare function.

Considering both cooperative and non-cooperative behavior, we found that technological improvements in productivity and adaptive capacity in one country will lead to increases in global emissions. Under non-cooperative behavior, this will negatively affect welfare in the other country, while the effect on global welfare is ambiguous. Under fully cooperative behavior, the effect on global welfare is positive. However, the effect of one country's productivity improvement on the other country's welfare remains negative, and the effect of one country's improvement in adaptive capacity on the other country's welfare is ambiguous.

Our findings imply that unilateral improvements in productivity and adaptive capacity have strategic significance and do not necessarily lead to mutual welfare improvements. They unambiguously raise the emissions not only in the country where the technological improvement takes place, but also globally. In promoting efforts to attain the technological improvements studied, decision makers should be aware of these effects.

Appendix

(1) At first we introduce the reduced welfare function for the home country. We have to solve

$$\max_A \; bB(E) - D\left(e\left(E+E^*\right), aA\right) - A.$$

The FOC is given by

$$-a D_A\left(e\left(E+E^*\right), aA\right) - 1 = 0.$$

We obtain $A = A(E+E^*, e, a)$ and

$$\frac{\partial A}{\partial E} = \frac{\partial A}{\partial E^*} = -\frac{eD_{AE}}{aD_{AA}} > 0, \quad \frac{\partial A}{\partial b} = 0, \quad \frac{\partial A}{\partial e} = -\frac{(E+E^*)D_{AE}}{aD_{AA}} > 0,$$
$$\frac{\partial A}{\partial a} = -\frac{D_A}{a^2 D_{AA}} - \frac{A}{a} \gtreqless 0.$$

Then

$$\hat{W} = bB(E) - D\left(e\left(E+E^*\right), aA\left(E+E^*, e, a\right)\right) - A\left(E+E^*, e, a\right).$$

(2) Welfare maximization

The FOC's are given by

$$bB'(E) - eD_E\left(e\left(E+E^*\right), aA\left(E+E^*, e, a\right)\right) - D_E^*\left(E+E^*, A^*\left(E+E^*\right)\right) = 0,$$
$$B^{*\prime}\left(E^*\right) - eD_E\left(e\left(E+E^*\right), aA\left(E+E^*, e, a\right)\right) - D_E^*\left(E+E^*, A^*\left(E+E^*\right)\right) = 0.$$

In the next step we totally differentiate these equations and get

$$B'db + bB''dE - D_E de - e\left(E+E^*\right)D_{EE}de - e^2 D_{EE}\left(dE+dE^*\right) - eAD_{EA}da$$
$$- eaD_{EA}\left(\frac{\partial A}{\partial E}\left(dE+dE^*\right) + \frac{\partial A}{\partial e}de + \frac{\partial A}{\partial a}da\right) - D_{EE}^*\left(dE+dE^*\right)$$
$$- D_{EA}^*\frac{\partial A^*}{\partial E}\left(dE+dE^*\right) = 0$$

and

$$B^{*\prime}dE^{*} - D_{E}de - e\left(E+E^{*}\right)D_{EE}de - e^{2}D_{EE}\left(dE+dE^{*}\right) - eAD_{EA}da - eaD_{EA}\left(\frac{\partial A}{\partial E}\left(dE+dE^{*}\right)+\frac{\partial A}{\partial e}de+\frac{\partial A}{\partial a}da\right) - D_{EE}^{*}\left(dE+dE^{*}\right) - D_{EA}^{*}\frac{\partial A^{*}}{\partial E}\left(dE+dE^{*}\right)=0.$$

Rearranging terms and rewriting these equations we obtain

$$M\begin{pmatrix} dE \\ dE^{*} \end{pmatrix} = C_{b}db + C_{e}de + C_{a}da$$

where

$$M = \begin{pmatrix} bB'' - (\upsilon+\upsilon^{*}) & -(\upsilon+\upsilon^{*}) \\ -(\upsilon+\upsilon^{*}) & B^{*\prime\prime} - (\upsilon+\upsilon^{*}) \end{pmatrix},$$

$$C_{b} = \begin{pmatrix} -B' \\ 0 \end{pmatrix},\quad C_{e} = \begin{pmatrix} D_{E} + (E+E^{*})\,\upsilon/e \\ D_{E} + (E+E^{*})\,\upsilon/e \end{pmatrix},$$

$$C_{a} = \begin{pmatrix} -\frac{D_{EA}D_{A}}{aD_{AA}} \\ -\frac{D_{EA}D_{A}}{aD_{AA}} \end{pmatrix},\quad \text{and}\quad \upsilon = e^{2}D_{EE} - e^{2}D_{EA}^{2}/D_{AA}.$$

The determinant of M is given by

$$\begin{aligned}\Delta_{M} &= \left(bB'' - \left(\upsilon+\upsilon^{*}\right)\right)\left(B^{*\prime\prime} - \left(\upsilon+\upsilon^{*}\right)\right) - \left(\upsilon+\upsilon^{*}\right)^{2} \\ &= bB''\left(B^{*\prime\prime} - \left(\upsilon+\upsilon^{*}\right)\right) - B^{*\prime\prime}\left(\upsilon+\upsilon^{*}\right).\end{aligned}$$

It is strictly positive if $\upsilon+\upsilon^{*} \geq 0$.
Then the inverse of M is given by

$$M^{-1} = \frac{1}{\Delta_{M}}\begin{pmatrix} B^{*\prime\prime} - (\upsilon+\upsilon^{*}) & (\upsilon+\upsilon^{*}) \\ (\upsilon+\upsilon^{*}) & bB'' - (\upsilon+\upsilon^{*}) \end{pmatrix}.$$

In the following we consider only those expressions whose sign is ambiguous for $\upsilon \geq 0$ and $\upsilon^{*} \geq 0$ (cf. Table 1).

(3) Preliminaries

In the optimum we have

$$\frac{\partial \hat{W}}{\partial E} + \frac{\partial \hat{W}^{*}}{\partial E} = 0 \Rightarrow \frac{\partial \hat{W}}{\partial E} = -\frac{\partial \hat{W}^{*}}{\partial E} = -\left(-D_{E}^{*}\right) = D_{E}^{*} > 0.$$

Analogously

$$\frac{\partial \hat{W}^{*}}{\partial E^{*}} > 0.$$

Then

$\frac{\partial \hat{W}}{\partial E^{*}} < 0$ and $\frac{\partial \hat{W}^{*}}{\partial E^{*}} < 0$ because of the FOC's.

$$\frac{\partial \hat{W}}{\partial e} = -\left(E+E^{*}\right)D_{E} < 0,\quad \frac{\partial \hat{W}}{\partial a} = -A\,D_{A} > 0.$$

(4) $db = 0, de > 0, da = 0$

$$\frac{dA}{de} = \frac{\partial A}{\partial (E + E^*)} \frac{d(E + E^*)}{de} + \frac{\partial A}{\partial e} = (+)(-) + (+) \gtreqless 0$$

$$\frac{d\hat{W}}{de} = \frac{\partial \hat{W}}{\partial E} \frac{dE}{de} + \frac{\partial \hat{W}}{\partial E^*} \frac{dE^*}{de} + \frac{\partial \hat{W}}{\partial e} = (+)(-) + (-)(-) + (-) \gtreqless 0$$

$$\frac{d\hat{W}^*}{de} = \frac{\partial \hat{W}^*}{\partial E} \frac{dE}{de} + \frac{\partial \hat{W}^*}{\partial E^*} \frac{dE^*}{de} = (-)(-) + (+)(-) \gtreqless 0$$

$$\frac{d\left(\hat{W} + \hat{W}^*\right)}{de} = -\left(E + E^*\right) D_E < 0.$$

(5) $db = 0, de = 0, da > 0$

$$\frac{dA}{da} = \frac{\partial A}{\partial (E + E^*)} \frac{d(E + E^*)}{da} + \frac{\partial A}{\partial a} = (+)(+) + (?) \gtreqless 0$$

$$\frac{d\hat{W}}{da} = \frac{\partial \hat{W}}{\partial E} \frac{dE}{da} + \frac{\partial \hat{W}}{\partial E^*} \frac{dE^*}{da} + \frac{\partial \hat{W}}{\partial a} = (+)(+) + (-)(+) + (+) \gtreqless 0$$

$$\frac{d\hat{W}^*}{da} = \frac{\partial \hat{W}^*}{\partial E} \frac{dE}{da} + \frac{\partial \hat{W}^*}{\partial E^*} \frac{dE^*}{da} = (-)(+) + (+)(+) \gtreqless 0.$$

(6) Nash equilibrium

The FOC's are given by

$$bB'(E) - eD_E\left(e\left(E + E^*\right), aA\left(E + E^*, e, a\right)\right) = 0$$

and

$$B^{*\prime}\left(E^*\right) - D_E^*\left(E + E^*, A^*\left(E + E^*\right)\right) = 0.$$

We differentiate these equations totally and get

$$\begin{aligned} &B'db + bB''dE - \ D_E de - e\left(E + E^*\right) D_{EE} de \\ &- e^2 D_{EE}\left(dE + dE^*\right) - eAD_{EA} da \\ &- eaD_{EA}\left(\frac{\partial A}{\partial E}\left(dE + dE^*\right) + \frac{\partial A}{\partial E} de + \frac{\partial A}{\partial a} da\right) = 0 \end{aligned}$$

and

$$B^{*\prime\prime} dE^* - \ D_{EE}^*\left(dE + dE^*\right) - D_{EA}^* \frac{\partial A^*}{\partial E}\left(dE + dE^*\right) = 0.$$

Rearranging terms and rewriting these equations we obtain

$$N\begin{pmatrix} dE \\ dE^* \end{pmatrix} = C_b db + C_e de + C_a da$$

where

$$N = \begin{pmatrix} bB'' - \upsilon & -\upsilon \\ -\upsilon^* & B^{*\prime\prime} - \upsilon^* \end{pmatrix},$$

$$C_b = \begin{pmatrix} -B' \\ 0 \end{pmatrix}, \ C_e = \begin{pmatrix} D_E + (E + E^*)\,\upsilon/e \\ 0 \end{pmatrix}, \quad \text{and} \quad C_a = \begin{pmatrix} -\frac{D_{EA} D_A}{aD_{AA}} \\ 0 \end{pmatrix}.$$

The determinant of N is given by

$$\Delta_N = \left(bB'' - \upsilon\right)\left(B^{*\prime\prime} - \upsilon^*\right) - \upsilon\upsilon^* = bB''\left(B^{*\prime\prime} - \upsilon^*\right) - B^{*\prime\prime}\upsilon.$$

It is strictly positive if $\upsilon \geq 0$.

The inverse of N is given by

$$N^{-1} = \frac{1}{\Delta_N}\begin{pmatrix} B^{*\prime\prime} - \upsilon^* & \upsilon \\ \upsilon^* & bB'' - \upsilon \end{pmatrix}.$$

Again we consider only those expressions whose sign is ambiguous for $\upsilon \geq 0$ and $\upsilon^* \geq 0$ (cf. Table 2).

(7) $db > 0, de = 0, da = 0$

$$\begin{aligned}\frac{d\left(\hat{W} + \hat{W}^*\right)}{db} &= \frac{\partial\hat{W}}{\partial E}\frac{dE}{db} + \frac{\partial\hat{W}}{\partial E^*}\frac{dE^*}{db} + \frac{\partial\hat{W}}{db} + \frac{\partial\hat{W}^*}{\partial E}\frac{dE}{db} + \frac{\partial\hat{W}^*}{\partial E^*}\frac{dE^*}{db} \\ &= 0 \cdot \frac{dE}{db} + (-)(-) + (+) + (-)(+) + 0\frac{dE^*}{db} \gtreqless 0.\end{aligned}$$

(8) $db = 0, de > 0, da = 0$

$$\frac{dA}{de} = \frac{\partial A}{\partial\left(E + E^*\right)}\frac{d\left(E + E^*\right)}{de} + \frac{\partial A}{\partial e} = (+)(-) + (+) \gtreqless 0$$

$$\begin{aligned}\frac{d\left(\hat{W} + \hat{W}^*\right)}{de} &= \frac{\partial\hat{W}}{\partial E}\frac{dE}{de} + \frac{\partial\hat{W}}{\partial E^*}\frac{dE^*}{de} + \frac{\partial\hat{W}}{de} + \frac{\partial\hat{W}^*}{\partial E}\frac{dE}{de} + \frac{\partial\hat{W}^*}{\partial E^*}\frac{dE^*}{de} \\ &= 0 \cdot \frac{dE}{de} + (-)(+) + (-) + (-)(-) + 0\frac{dE^*}{de} \gtreqless 0.\end{aligned}$$

(9) $db = 0, de = 0, da > 0$

Analogously to (8).

Acknowledgments We thank Michael Rauscher and two anonymous referees for helpful comments and suggestions and Jan Kühling for editorial assistance.

References

Barrett S (2008) Dikes v. Windmills: climate treaties and adaptation. Mimeo, Johns Hopkins University School of Advanced International Studies, Baltimore

Bulow JI, Geanakoplos JD, Klemperer PD (1985) Multimarket oligopoly: strategic substitutes and complements. J Polit Econ 93:488–511

Ebert U, Welsch H (2011) Optimal response functions in global pollution problems can be upward sloping: accounting for adaptation. Environ Econ Policy Studies 13:129–138

Finus M, Maus S (2008) Modesty may pay!. J Public Econ Theory 10:801–826

Hoel M (1991) Global environmental problems: the effects of unilateral actions taken by one country. J Environ Econ Manage 20:55–70

Ingham A, Ma J, Ulph A (2005) Can adaptation and mitigation be complements? Tyndall Centre for Climate Change Research, Working paper 79

Ingham A, Ma J, Ulph A (2007) Climate change, mitigation and adaptation with uncertainty and learning. Energy Policy 35:5354–5369

IPCC (2007) Intergovernmental panel on climate change: climate change 2007—Fourth assessment report, Cambridge: Cambridge University Press

Kane S, Shogren JF (2000) Linking adaptation and mitigation in climate change policy. Climat Chang 45:75–102

Lecoq F, Shalizi Z (2007) Balancing expenditures on mitigation of and adaptation to climate change: an exploration of issues relevant to developing countries, Policy research working paper series 4299, The World Bank

Rosen JB (1965) Existence and uniqueness of equilibrium points for concave N-person games. Econometrica 33:520–534

Shibata H, Winrich JS (1983) Control of pollution when the offended defend themselves. Economica 50:425–437

Tol R (2005) Adaptation and mitigation: trade-offs in substance and methods. Environ Sci Policy 8:572–578

Tulkens H, van Steenberghe V (2009) Mitigation, adaptation, suffering: in search of the right mix in the face of climate change, FEEM Nota di Lavoro 79.2009

Welsch H (1993) An equilibrium framework for global pollution problems. J Environ Econ Manag 25:S64–S79

Zehaie F (2009) The timing and strategic role of self-protection. Environ Resour Econ 44:337–350