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Abstract

Policy advocates frequently request for unilateral action to push forward climate protection in international negotiations. It is yet conventional wisdom in environmental economics that unilateral action does not pay for the first mover due to free-riding behavior of the other countries. How does this analysis change if there is a further option at hand: off-setting damages from joint emissions by individual adaptation measures?

Adaptation to climate change plays an increasingly role in the international negotiations under the UNFCCC. This paper shows that when adaptation is considered as an explicit decision variable, and unilateral action is framed as a Stackelberg game, the resulting convexity properties imply (when the follower has a specific property) that total emissions are reduced to the benefit of all countries in the game equilibrium. When countries play a game of timing in a period before emission and adaptation decisions – to determine who takes the role of the Stackelberg leader – it is shown that a country with this specific property indeed becomes the follower. The equilibrium of the overall game is Pareto superior to the non-cooperative Nash solution.

Keywords: international environemental problems; climate change; Stackelberg game; convexity.

1 Introduction

Solving international environmental problems requires the reduction of damaging emissions, e.g. greenhouse gases or chlorofluorocarbon (CFC). As reducing such

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emissions is a provision of a public good, it is difficult to reach an agreement on emission abatement. Due to emission leakage, if one country would unilaterally reduce emissions, it has to be expected that others expand their emissions as a reaction. How does this analysis change if there is a further option at hand: off-setting damages from joint emissions by individual adaptation measures?

Taking climate change as a prime example, this paper refers to adaptation as "adjustments [...] in response to actual or expected climatic stimuli or their effects that moderate harm or exploit beneficial opportunities" (e.g. IPCC, 2007). Thus, in contrast to emissions abatement, adaptation considers a negative external effect as given, and aims at reducing its damage. Such activities are also called defensive, protective measures or averting behaviour in the economic literature (e.g. Baumol, 1972; Butler and Maher, 1986; McKitrick and Collinge, 2002). This thread of research gets new relevance as adaptation to climate change plays an increasing role in the international negotiations under the UNFCCC (see, e.g. Haites, 2011).

Adaptation is frequently regarded as having private good properties (e.g. Nordhaus, 1990; Cropper and Oates, 1992). Then, it is expected that adaptation has no effect on the strategic analysis of international environmental problems. There are yet at least two considerations that point towards a qualification. First, this picture might change if multi stage games are considered. It was a political argument in the 1990s that if too much effort is put to adapt to climate change, this might lead to less effort to abate greenhouse gas emissions (e.g. Pielke et al., 2007). Can this be a credible threat in the climate negotiations? This, at least, depends on the timing of adaptation and mitigation decisions. Different time structures are also considered in the established literature on international environmental agreements, where, e.g., a coalition takes the role of a Stackelberg leader in reducing emissions (starting with Barrett, 1994). What if adaptation plays a role in such a setting as well? Second, some fundamental considerations on the effects of adaptation show that standard convexity properties of damage functions may change (e.g. Baumol, 1972). To my knowledge, this has not been considered in the literature on international environmental agreements yet. If unilateral emission reductions lead to *increasing* marginal damages for other countries, they might reduce emissions as well. This paper shows that this effect is indeed possible, and analyses the specific conditions for its appearance. It is further determined how this changes the equilibrium of a specific multi-stage game of international emission reductions.

Although the effects of adaptation have been mostly neglected in the established environmental economics literature (see, e.g. Baumol, 1972; Butler and Maher, 1986, for early exceptions), research on the economics of adaptation is currently in a very fluent stage. This applies, for example, to the questions of timing in global environmental problems. In a setting without adaptation, the effects of unilateral action were transparently brought to front by Hoel (1991). He considered the (negative) slope of the reaction functions in a Nash game of emissions reductions, and investigated the consequences of one country having preferences for lower total emissions. As a reaction, the other country expands its emissions. Zehaie (2009) addresses questions of timing when also adaptation is an option. He shows that adaptation has no strategic effect if it is undertaken after or simulteneously with emission reductions. If adaptation happens first, there are strategic effects. This type of timing issue does, however, not address the question of unilateral action. Also the seminal work on international environmental agreements does not consider adaptation. For symmetric countries and specific parameterizations, Carraro (1993) investigates coalition stability when there is a Nash game between the coalition and the non-signatories, while for Barrett (1994) the signatories jointly become the Stackelberg leader. This can be interpreted as unilateral action in the game stage after coalition formation. Barrett (2008) undertook a first attempt to extend this to the case where adaptation is possible; with damages and adaptation costs linear in the amount of adaptation. Also Marrouch and Chaudhuri (2011) investigate the stability of an international environmental agreement in a similar setting with a quadratic damage that decreases linearly in the amount of adaptation. As adaptation reduces marginal damage costs (and thus emission abatement), coalition stability may improve. For another linear-quadratic damage function, Buob and Siegenthaler (2011) analyse a model where adaptation decreases coalition stability. de Bruin et al. (2011) analyse a multi-stage game containing coalition formation, preceded by the adaptation decision. Again, damages are linear-quadratic. They determine the stable coalitions for a model with heterogenous countries/regions that is calibrated to the Ad-RICE integrated assessment model. Most of these studies work with very specific damage functions. A more general setting is provided by Ebert and Welsch (2011) who investigate a large class of damage functions that explicitly model the effect of adaptation expenditures. They show that reaction functions in a game with two countries may become upward-sloping under specific conditions. This contrasts the Hoel (1991) result. These specific conditions will play a crucial role in this paper.

This paper contributes by isolating a certain effect of adaptation for a general class of damage functions. To do so, the basic temporal structure of unilateral action is represented by a Stackelberg assumption. We simplify by concentrating on the case of two countries. To our knowledge, our setting is unique in that it both explicitly represents an adaptation decision with a general class of damage functions, and considers unilateral action.

For exposition, section 2 will outlay established results on Nash and Stackelberg emission reduction games without adaptation, and on Nash games with adaptation. This section also defines α and β type countries, which is an important distinction for the whole paper. Section 3 shows how the equilibirium of a Stackelberg game with adaptation depends on the countries' types. The subsequent section considers a more complex setup, where a game of timing is played before a Stackelberg or Nash equilibrium is established. Section 4 presents some additional results that help interpreting the two country types and that links the results back to the literature without adaptation. A discussion section concludes.

2 Basic emission games

This section recalls some results on two country emissions games with and without adaptation. This is needed as an exposition for the setup of this paper, partially as reference for the proofs, and to contrast them with established analysis.

2.1 Nash and Stackelberg equilibrium without adaptation

We first set up a basic emissions game with payoff functions

$$\pi_i(e_i, e_{-i}) = B_i(e_i) - L_i(e_i + e_{-i}), \tag{1}$$

where e_i represents the emissions of country $i = 1, \ldots, N$, and e_{-i} the total emissions of all other countries. The individual benefits from individual emissions B_i are net of the individual damages L_i from total emissions $e = e_i + e_{-i}$. As standard convexity properties

$$\forall i : B_i', L_i', L_i'' > 0, L_i'' < 0, \tag{2}$$

is assumed. If the functions also behave properly at the limits, an interior Nash equilibrium is given by

$$\forall i : B_i' = L_i'. \tag{3}$$

For simplicity, we assume in the following that this interior solution exists, and set $N = 2$. Then, the slope of the reaction functions $e_i = R_i(e_{-i})$ are of the form

$$R_i' = \frac{L_i''}{B_i'' - L_i''} \in [-1, 0], \tag{4}$$

(see Hoel, 1991). The latter paper considers unilateral action by assuming that country $i = 1$, by some reason, has a modified pay-off function that considers a benefit from total abatement of both countries. Thus, its emissions decrease below the Nash equilibrium. Since country $i = 2$ remains on its original reaction curve, its emissions e_2 increase (although to a lesser extent than e_1 decreases): there is a loss from leakage. The opposite case of unilaterally increasing emissions is not considered by Hoel (1991) as this is regarded as politically unlikely.

An alternative way of considering unilateral action is a Stackelberg setup (a case not considered in the Hoel (1991) contribution). First, country $i = 1$ sets its emission level as a leader, while the Stackelberg follower $i = 2$ reacts to this decision. The follower reacts as in the Nash setup, i.e. $e_2 = R_2(e_1)$ is determined by $B_2'(e_2) = L_2'(e_1 + e_2)$ as before. The Stackelberg leader consequently solves the optimiziation problem

$$\max_{e_1} B_1(e_1) - L_1(e_1 + R_2(e_1)), \tag{5}$$

such that the first order condition yields

$$B_1' = (1 + R_2')L_1'. \tag{6}$$

By putting this together with Eq. (3) and Eq. (4), the solution of the first oder conditions can be equivalently described by the system of two equations

$$B_2' = L_2', \tag{7}$$

$$\frac{L_2''}{B_2'' - L_2''} = \frac{B_1' - L_1'}{L_1'}. \tag{8}$$

The following intuitive result follows from these conditions:

Proposition 1 *Under convexity assumptions Eq. (2), the Stackelberg equilibrium of the emissions game defined by Eq. (1) leads to higher total emissions e than in the Nash equilibrium. The leader's emissions are higher, and the follower's are lower than in the Nash equilibrium.*

Proof 1 *The left-hand side of Eq. (8) is negative due to Eq. (4) (except for the limiting case $R_2' = 0$). Thus, if evaluated at the solution of the first order conditions, $\partial_{e_1}\pi_1 = B_1' - L_1' < 0$. Since also $B_1'' - L_1'' < 0$ by Eq. (2), this can only be the case if the leader's emissions are above its level in the Nash equilibrium (where $B_1' - L_1' = 0$).*

The solution of Eq. (7) and Eq. (8) only represents the Stackelberg equilibrium if sufficiency is guaranteed. If the first order condition Eq. (6) for the Stackelberg equilibrium is evaluated at the place of the Nash equilibrium, we obtain

$$\partial_{e_1}\pi_1 = B_1' - L_1' - R_2'L_1' > B_1' - L_1' = 0. \tag{9}$$

The inequality follows from the negative slope of the reaction function Eq. (4) and Eq. (2). This shows that when the leader expands its emissions starting from the Nash level, its payoff increases at least locally. Since it has been shown that the necessary conditions are met at emissions above the Nash level, it must therefore exist at least one local optimum that improves the leader's payoff compared to the Nash equilibrium.

Thus, the first order conditions Eq. (7) and Eq. (8) indeed describe the Stackelberg equilibrium. As a consequence of the leader expanding its emissions, the follower reduces its emissions as response, since $R_2' < 0$. As also $-1 < R_2'$, this reduction is smaller than the leaders increase. Consequently, total emissions increase.

Thus, the Stackelberg leader can improve its payoff by emitting more than would be optimal under Nash conditions. This forces the follower to reduce its emissions, and thus reducing its payoff. Unilateral action in a Stackelberg framework has no benefitial effect for overall emission abatement. Or, to put it in different words, if one country wants to contribute to emission reductions by unilateral action, she would not be individually rational. This critical conclusion is in line with the results of Hoel (1991), yet with different assumptions about the game structure.

2.2 Nash equilibrium with adaptation

We now consider whether this results carriers over to an emissions game where adaptation to pollution is considered as a further decision variable. In this case, Ebert and Welsch (2011) show that the slope of the reaction function may become positive. Before builing the further argument on that, we first recall this result by introducing *extended* damage functions $D_i(e, a_i)$, with the partial derivatives

$$\begin{aligned} \partial_e D_i > 0, \partial_{ee} D_i > 0, \\ \partial_a D_i < 0, \partial_{aa} D_i > 0, \\ \partial_{ea} D_i = \partial_{ae} D_i < 0. \end{aligned} \tag{10}$$

Damage increases convexly with emissions e, and decreases convexly with the expenditures for adaptation a_i. The benefit functions $B_i(e_i)$ are assumed to be strictly increasing and concave. Furthermore, the convexity condition

$$\partial_{ee} D_i - \frac{\partial_{ea} D_i^2}{\partial_{aa} D_i} - B_i'' > 0, \tag{11}$$

is assumed to hold for every country i. This formulation defines the marginal adaptation costs to be identical to unity. This avoids the well known problems in defining a common metric of the "amount of adaptation" (see, e.g. Füssel and Klein, 2006). Instead, we consider a_i as expenditures the effect of which partially determines the quantitative properties of the extended damage function. The payoff function is given by

$$\pi_i(e_i, e_{-i}, a_i) = B_i(e_i) - D_i(e_i + e_{-i}, a_i) - a_i. \tag{12}$$

As every countries decides on two variables (its emissions and its adaptation expenditures), it is crucial to be careful about the time structure of the game. We assume that all countries simulatenously decide about both variables: their strategies are vectors. In a Nash equilibrium the vectors are selected such that there is no incentive to unilaterally deviate from the selection. The Nash equilibrium is characterized by the conditions

$$\forall i : \partial_e D_i(e, a_i) = B_i'(e_i), \tag{13}$$

$$\partial_a D_i(e, a_i) = -1. \tag{14}$$

Solving these equations jointly for all countries yields the emission and adaptation decisions. By just solving the second condition, Eq. (14) determines *optimal adaptation decision functions* $a_i = A_i(e)$, that depend on the level of total emissions e. Substituting this optimal adaptation decision function into the first condition Eq. (13) and solving for e_i yields the reaction functions $e_i = R_i(e_{-i})$.

Inspecting A_i, R_i shows a crucial feature: the decision of country i only depends on the *emission* decision of the other countries, but *not* on their adaptation decision. First, this indicates that adaptation may only have a limited strategic role — this statement will yet be qualified in the following. Second, the Nash equilbrium is identical to the solution of a two stage game where all countries first simultaneously decide on their emissions, and in the second stage on their adaptation expenditures (the latter is discussed by Ebert and Welsch, 2011). Formally, if e_i, e_{-i}, a_i jointly solve Eq. (13) and Eq. (14), this is equivalent to

$$\begin{aligned} B_i'(e_i) &= \partial_e D_i(e_i + e_{-i}, A_i(e_i + e_{-i})) \quad \text{(stage 1)}, \\ a_i &= A_i(e_i + e_{-i}) \quad \text{(stage 2)}. \end{aligned} \tag{15}$$

On the other hand, for a two stage game where adaptation decisions are made first, and then emission decision follow, the solution can change (this is a simple explanation of the result of Zehaie, 2009).

In the following, by restricting again to the $N = 2$ case, we denote the Nash equilibrium by $(e_1^\bullet, a_1^\bullet, e_2^\bullet, a_2^\bullet)$. Due to inclusion of adaptation, the reaction function $e_i = R_i(e_{-i})$ now has the slope

$$R_i'(e_{-i}) = \frac{\nu_i}{B_i'' - \nu_i} \in [-1, \infty], \tag{16}$$

$$\nu_i := \partial_{ee} D_i - \frac{\partial_{ea} D_i^2}{\partial_{aa} D_i}, \tag{17}$$

(see Ebert and Welsch, 2011). If $\nu_i > 0$, the reaction function R_i is downward sloping as in the case without adaptation. Interestingly, if $\nu_i < 0$ the reaction function increases. As this is a crucial observation for the paper, we refer to these cases in the following as

$$\alpha\text{-type country if} \quad \nu_i > 0, \tag{18}$$

$$\beta\text{-type country if} \quad \nu_i < 0. \tag{19}$$

The existence of β-type countries is becomes possible, depending on the paramterization, due to the indirect effects of adaptation on the emission decision. For the limiting case $\nu_i = 0$ the emission reaction is independent from the emissions decisions of the other player. Due to the implicit function theorem, Eq. (14) determines

$$A_i'(e) = -\frac{\partial_{ae} D_i}{\partial_{aa} D_i} > 0. \tag{20}$$

What are the consequences for the prospects of unilateral action when there are both α-type and β-type countries with positively-sloped reaction functions? If all countries are β-type, an unilateral emission reduction by one of them would lead to a reduction of the other. But can unilateral action also become individually rational in this context? We now determine this for a Stackelberg setup.

3 Stackelberg equilibrium with adaptation

We now come to the core analysis of the paper that combines the different features of the previous section: unilateral action as a Stackelberg game with adaptation. The cases above will be important benchmarks in the argument.

We first consider that country 1 is the Stackelberg leader by announcing its emissions e_1 and adaptation expenditures a_1 in the first stage of the game. In a second stage, country 2 reacts by determining its level of emissions e_2 and adaptation expenditures a_2. As before, we assume payoff functions $\pi_i(e_i, e_{-i}, a_i) = B_i(e_i) - D_i(e_i + e_{-i}, a_i) - a_i$, with extended damage functions D_i and stick to the convexity properties Eq. (10) and Eq. (11).

By backward induction, we start with the second stage. The follower maximizes π_2 with respect e_2, a_2 and takes the first stage decision e_1, a_1 as given parameters. The problem is formally the same as determining the reaction function R_2 in the Nash case (compare Eq. (13), Eq. (14)). Of course, also the optimal adaptation decision function of the follower $a_2 = A_2(e)$ is the same function. We thus obtain

$$R_2' = \frac{\nu_2}{B_2'' - \nu_2} \in [-1, \infty], \tag{21}$$

$$A_2' = -\frac{\partial_{ae}\tilde{D}_2}{\partial_{aa}\tilde{D}_2}. \tag{22}$$

The leader then determines

$$\max_{e_1, a_1} \pi_1 = B_1(e_1) - \tilde{D}_1(e_1 + R_2(e_1), a_1) - a_1, \tag{23}$$

in the first stage of the game. Interestingly, the outcome of the decision depends on the properties of the follower:

Proposition 2 *Assume payoff functions $\pi_i = B_i - D_i - a_i$ that obey the convexity properties Eq. (10) and Eq. (11). If a vector $(e_1^\circ, a_1^\circ, e_2^\circ, a_2^\circ)$ exists that satifies the first order conditions*

$$0 = B_1'(e_1^\circ) - (1 + R_2'(e_1^\circ))\, \partial_e \tilde{D}_1(e_1^\circ + R_2(e_1^\circ), a_1^\circ), \tag{24}$$

$$0 = \partial_a \tilde{D}_1(e_1^\circ + R_2(e_1^\circ), a_1^\circ) + 1, \tag{25}$$

then a Stackelberg equilibrium exists. In this equilibrium, the first order conditions Eq. (24) and Eq. (25) hold.

Let $(e_1^\bullet, a_1^\bullet, e_2^\bullet, a_2^\bullet)$ denote the Nash equilibrium. There are two cases:

1. *Assuming an α type follower, total emissions in the Stackelberg equilibrium are above the level of the Nash equilibrium. It holds that*

$$e_1^\bullet < e_1^\circ, \quad e_2^\circ < e_2^\bullet, \quad e^\bullet < e^\circ, \quad \pi_1^\bullet < \pi_1^\circ. \tag{26}$$

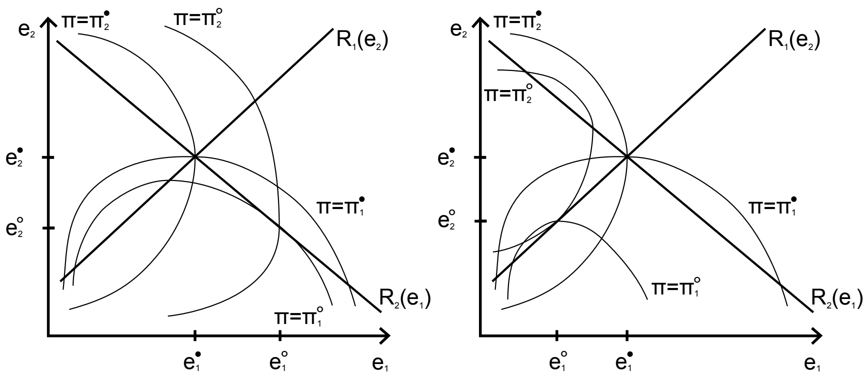

Figure 1: Nash and Stackelberg equilibrium if country 1 is of β-type, and country 2 of α-type. In the first case (left), the α-type country is the follower, the follower in the second case (right) is a β-type country.

2. *Assuming a β type follower, total emissions are lower than in the Nash equilibrium. It holds that*

$$e_1^\circ < e_1^\bullet, \quad e_2^\circ < e_2^\bullet, \quad e^\circ < e^\bullet, \quad \pi_1^\bullet < \pi_1^\circ. \tag{27}$$

The dependency on the properties of the follower is illustrated in Fig. 1. It shows the special case where country 2 is an α-type country (with decreasing reaction function R_2), while the other is a β-type country (with increasing reaction function R_2). The figures compare the equilibria depending on which country is the Stackelberg leader with the Nash equilibrium. The latter is at the intersection of both reaction functions. Due to the convexity assumptions, isopayoff curves are U-shaped, and the curves $\pi_1 = \pi_1^\bullet, \pi_2 = \pi_2^\bullet$ go through the Nash equilibrium. Payoffs for country 1 are higher below the $\pi_1 = \pi_1^\bullet$ curve, while the payoffs for country 2 increase to the left of $\pi_2 = \pi_2^\bullet$. Thus, the points between both curves to the lower left represent Pareto improvements compared to the Nash equilibrium.

Consider the left graph in Fig. 1 first, where country 1 is the leader, and the follower is of the α type. The leader then selects e_1 under the assumption that the follower reacts with emissions on the reaction function R_2. The leader's maximum payoff is thus reached where an isopayoff curve $\pi_1 = \pi_1^\circ$ is tangent to R_2. This is only possible if the leader expands its emissions, $e_1^\bullet < e_1^\circ$, and improves the leader's payoff in comparison to the Nash equilibrium to $\pi_1^\circ > \pi_1^\bullet$. As the slope of R_2 is less than unity, total emissions increase $e^\bullet < e^\circ$. This reduces the followers payoff to $\pi_2^\circ < \pi_2^\bullet$. This case therefore resembles the pessimistic standard result without adaptation shown in Prop. 1: unilateral action in the Stackelberg sense produces too much emissions and does not result in a Pareto improvement.

This is different in the case illustrated by the right graph in Fig. 1, where country 2 is the leader, and the follower is a β-type country. Then, emissions e_2 are selected such that the isopayoff curve $\pi_1 = \pi_1^\circ$ is tangent to the reaction function R_1, which leads to the emission reduction $e_2^\circ < e_2^\bullet$. Due to the β-type, the follower also reacts with emission reductions. In sum, total emission decrease to $e^\circ < e^\bullet$, and a Pareto improvement is achieved as both countries increase their payoff.

Proof 2 *We first characterize the necessary conditions for an (interior) Stackelberg equilibria to compare emissions with the Nash equilibrium for both cases. We then turn to the sufficiency of Eq. (24) and Eq. (25). This also establishes the ordinal relation between Nash and Stackelberg equilibrium for the payoffs.*

In the Stackelberg game, country 1 anticipates the reaction function of the follower, so that solving Eq. (23) for a_1 yields the first order condition Eq. (25) that determines the same optimal adaptation decision function $a_1 = A_1(e)$ as in the Nash game. Then, substituting this into Eq. (23) and differentiating with respect to e_1 leads to

$$\begin{aligned} B_1'(e_1) &= \frac{d}{de_1}[D_1(e_1 + R_2(e_1), A_1(e_1 + R_2(e_1))) + A_1(e_1 + R_2(e_1))] \\ &= \partial_e D_1(1 + R_2') + \partial_a D_1 A_1'(1 + R_2') + A_1'(1 + R_2') \\ &= (1 + R_2')(\partial_e D_1 + (\partial_a D_1 + 1)A_1') \\ &= (1 + R_2')\partial_e D_1(e_1 + R_2(e_1), A_1(e_1 + R_2(e_1))). \end{aligned} \tag{28}$$

The last equality follows from Eq. (25). Thus, Eq. (24) necessarily holds for an interior solution.

In the Nash game, country 1 selects e_1, a_1 according to Eq. (15), i.e. $B_1'(e_1) = \partial_e D_1(e_1 + e_2, A_1(e_1 + e_2))$. As country 2 selects its emissions according to its reaction function $e_2 = R_2(e_1)$, the Nash equilibrium is characterized by

$$B_1'(e_1) = \partial_e D_1(e_1 + R_2(e_1), A_1(e_1 + R_2(e_1))). \tag{29}$$

Now turn to the two cases. If the follower is an α-type country, $R_2' < 0$, so that Eq. (28) is smaller than Eq. (29). Thus, since B_1' is strictly decreasing in e_1, it must hold that $e_1^\bullet < e_1^\circ$. As the follower country has a downward sloping reaction function, it reduces its emissions compared to the Nash equilibrium. As also $-1 < R_2'$, these reductions are smaller than the leaders additional emissions, the total emissions are higher for the Stackelberg equilibrium.

In contrast, if the follower is a β-type contry, $R_2' > 0$ implies that Eq. (28) becomes larger than Eq. (29). Thus, in contrast to the other case, $e_1^\circ < e_1^\bullet$. Now, the follower country has an upward sloping reaction function, so that it reduces emissions below the Nash equilibrium likewise. Also total emissions are consequently lower in the Stackelberg equilibrium.

Finally, turn to the sufficiency of the first order conditions. First note that Eq. (25) indeed optimizes payoffs for any given level of total emissions e, since

$\frac{d^2}{da_1 a_1}\pi_1 = -\partial_{aa} D_1 < 0$. *Second, due to Eq. (28)*

$$\frac{d}{de_1}\pi_1(e_1, R_2(e_1), A_1(e_1 + R_2(e_1))) = B_1' - (1 + R_2')\partial_e D_1, \quad (30)$$
$$= B_1' - \partial_e D_1 - R_2' \partial_e D_1.$$

When this derivative is evaluated at the Nash equilibrium, the first two terms on the right hand side cancel out, such that

$$\frac{d}{de_1}\pi_1(e_1^\bullet, R_2(e_1^\bullet), A_1(e^\bullet)) = -R_2' \partial_e D_1. \quad (31)$$

Since D_1 increases with e, the local change of payoff in the Nash equilibrium has the opposite sign of R_2'. If the follower is an α-type country (such that $e_1^\circ > e_1^\bullet$), increasing emissions improve the leader's payoff at least locally. This guarantees the existence of an optimum, as - due to continuity - payoff only ceases to increase further if, at last, e_1° is reached.

If there are multiple vectors that satisfy the first order conditions, then one of them must describe the optimum. If the follower is a β type country, the analogue argument can be made if emissions e_1 are decreased below $e_1^\bullet$. Thus, a decision e_1°, a_1° from the first oder conditions indeed optimizes (and strictly improves) payoff for the Stackelberg leader in both cases.

It is not straightforward to establish existence and uniqueness of the solution to the first order conditions. By further differentiating Eq. (30),

$$\frac{d^2}{de_1 e_1}\pi_1 = B_1'' - (1 + R_2')^2 \nu_1 - R_2'' \partial_e D_1, \quad (32)$$

is obtained. Negativity cannot be generally established. The sign of R_2'' involves the third derivates of the extended damage function, about which no assumptions have been imposed.

To sum up this section, there is a case for unilateral action contributing to the solution of global environmental problems. If the follower in this game is of the β type, unilateral action achieves a Pareto improvement compared to the non-cooperative Nash solution. When there are both actors of the α and β type, the result depends on who takes the lead. This is investigated in the next section.

4 Who takes Stackelberg leadership?

The previous analysis takes the roles of the Stackelberg leader and follower as given. There might be indeed historical or other reasons that define these roles at a given time. In this section, however, we analyse the case where the timing of the game on emissions and adaptation in undetermined from the on-set. In a similar veign as

Heugues (2011), we assume a multi-stage game where the first stage is a game of timing. Each country can decide on whether to act now or to wait. If both countries act now or wait, a Nash game is played at the later stages. If just on country decides to act now, it becomes the Stackelberg leader.

In detail, the game structure (for two countries) is a follows:

Stage 1: Country i selects a strategy u_i form the set $\{F, L\}$, depending on whether it want to become the Follower (wait) or the Leader (act now). The outcome of this stage determines the game structure of the next stages.

Case (1): If $u_1 = u_2$ at stage 1, countries play a Nash game.

Stage 2: The decision variables $(e_1^\bullet, a_1^\bullet, e_2^\bullet, a_2^\bullet)$ are simultaneously set.

Case (2): If $u_1 = L, u_2 = F$, then countries play a Stackelberg game with country 1 as leader (according to Prop. 2).

Stage 2: Country 1 decides on (e_1°, a_1°).

Stage 3: Country 2 decides on (e_2°, a_2°).

Case (3): If $u_1 = F, u_2 = L$, then countries play a Stackelberg game (according to Prop. 2). Roles from case (2) are reversed.

Stage 2: Country 2 decides on (e_2°, a_2°).

Stage 3: Country 1 decides on (e_1°, a_1°).

The payoffs of the countries are determined by the payoffs they get in the (Nash or Stackelberg) equilibrium after the final stage. This game can be solved by backward induction, where the solution of the stages 2 and 3 are already determined above for all cases.

This game can be solved for different settings. We first concentrate on the most interesting, heterogeneous case with one α-type and one β-type country. After that, we also determine the solution if both countries are α-type or both are β-type.

Proposition 3 *Assume (without loss of generality) that country 1 is β-type, and country 2 is α-type. The other assumptions according to Eq. (10) and Eq. (11) hold, and payoffs are given by $\pi_i = B_i - D_i - a_i$. Then, the equilibrium of the multi-stage game is as follows: The α-type country 2 becomes the Stackelberg leader, while the β-Type country becomes the follower. Total emissions are below the level of the non-cooperative Nash solution, and the payoffs are Pareto-superior to the non-cooperative Nash solution. The bimatrix of the game of timing (stage 1) is given by Fig. 2.*

This result basically rests on how the Stackelberg equilibria change payoffs in comparison to the non-cooperative Nash equilibrium. Prop. 2 has shown that this depends on the type of the Stackelberg follower. When the follower is an α-type country, the leader expands emissions to improve its payoff at the expense of the follower. If, in contrast, the follower is β-type, the leader reduces emissions, such that the follower reduces emissions as well. So, both countries improve their payoff compared to the Nash equilibrium. In this case the β country is willing to let the α country take the lead. This situation is represented in the payoff matrix of the stage 1 game (see Fig. 2).

This is the positive result of this paper. In the game equilibrium total emissions come closer to the social optimum. This improves the situation for both countries. If it is not determined from the onset whether the "right" coutnry takes the lead, the equilibrium of the game of timing fortunately leads to a configuration with Pareto improvement. When there are heterogeneous countries, the α countries undertake unilateral action to the benefit of all.

		Country 2 (α-type) Follower	Leader
Country 1 (β-type)	Follower	Result: Nash $e = e^\bullet$ $\pi_1 = \pi_1^\bullet$ $\pi_2 = \pi_2^\bullet$	Result: 2 is Leader $e < e^\bullet$ $\pi_1 = \pi_1^2 > \pi_1^\bullet$ $\pi_2 = \pi_2^2 > \pi_1^\bullet$
	Leader	Result: 1 is Leader $e > e^\bullet$ $\pi_1 = \pi_1^1 > \pi_1^\bullet$ $\pi_2 = \pi_2^1 < \pi_2^\bullet$	Result: Nash $e = e^\bullet$ $\pi_1 = \pi_1^\bullet$ $\pi_2 = \pi_2^\bullet$

Figure 2: Payoff matrix of stage 1 game and resulting total emissions. The Nash equilibrium lies in the upper right cell.

Proof 3 *We show this result by deriving the payoff matrix of the stage 1 game, and the ordinal relations as shown in Fig. 2. If stage 1 leads to case (1), payoffs are determined from the Nash equilbrium in stage 2. These are, again, denoted by $\pi_i^\bullet$, and derived from Eq. (13) and Eq. (14). If stage 1 leads to case (2) or (3), payoffs are determined from the appropriate Stackelberg equilibrium as characterized in Prop. 2. The term π_i^j denotes the equilibrium payoff of country i, supposed that j is the Stackelberg leader. Once the relationships between the different payoffs of the later stages are shown, inspection of Fig. 2 proves that the α country 2 plays 'Leader' as a dominant strategy, while the β country 1 always reacts by playing the opposite strategy of country 2. The α country becomes the leader, and the β country the follower in the stage 1 equilibrium.*

First consider case (2) where country 1 is the leader (lower left cell in Fig. 2). Then, it was already shown in Prop. 2 that $\pi_1^\bullet < \pi_1^1$, since the follower is an α country. Total emissions and the emissions of the leader increase. In contrast, $\pi_2^1 < \pi_2^\bullet$, by the following reasons. If the leader expands emissions, the follower *reduces emissions along its reaction curve. Observe that*

$$\begin{aligned}\frac{d}{de_1}\pi_2(e_1, R_2(e_1), A_2(e_1 + R_2(e_1))) &= \partial_{e_1}\pi_2 + \partial_{e_2}\pi_2 R_2' + \partial_a \pi_2 A'(1 + R_2') \\ &= \partial_{e_1}\pi_2 < 0. \end{aligned} \tag{33}$$

The second equality is due to the first order conditions $\partial_{e_2}\pi_2 = 0$ and $\partial_a\pi_2 = 0$ on the reaction function of the follower. Thus, the increase of the leaders' emissions is associated with a lower payoff for the follower country 2.

Now consider case (1), where the α country 2 is the leader (upper right cell in Fig. 2). As the follower is a β-type country, Prop. 2 shows that total emissions are below the Nash equilibrium. The leader improves its payoff by reducing its own emissions. As a consequence (symmetrically to Eq. (33)),

$$\frac{d}{de_2}\pi_1(R_1(e_2), e_2, A_1(e_2 + R_1(e_2))) = \partial_{e_1}\pi_1 < 0,$$

such that the follower benefits.

These considerations show all necessary ordinal relations as given in Fig. 2.

We now turn to the cases where both countries are of the same type.

Proposition 4 *Assume that both countries are α type an the other assumptions as in Prop. 3 hold. Then, both play 'Leader' as dominant strategy in the stage 1 game. This leads to the non-cooperative Nash solution.*

Proof 4 *If case (2) or (3) result from the stage 1 game, the follower would always be an α country. Thus, by Prop. 2, taking the role of the leader always improves the payoffs compared to the Nash equilibrium. The proof of Prop. 3 for case (2) shows that taking the role of the follower disimproves payoff for both countries. Thus, the non-cooperative Nash equilibrium results.*

Proposition 5 *Assume that both countries are β type an the other assumptions as in Prop. 3 hold. This leads to two game equilibria, where one country plays 'Leader', and the other 'Follower' in the stage 1 game. Both equilibria reduce total emissions and lead to a Pareto improvement compared to the non-cooperative Nash solution.*

Proof 5 *Since the follower is always a β country, the same considerations as for case (1) in the proof of Prop. 3 apply. Thus, in the stage 1 game, both countries prefer the opposite strategy of the other country.*

5 On the interpretation of β-type countries

An appropriate interpretation of being a β country is not straigtforward. Ebert and Welsch (2011) discuss a positive value for ν_i as a kind of low vulnerability to emissions. We now further explain the interpretation and the strategic role of adaptation at the same time by considering the relation between the *extended* damage functions $D_i(e, a_i)$ and the *optimized* damage functions, defined as (cf. Tulkens and van Steenberghe, 2009)

$$\tilde{D}_i(e) := \min_{a_i} D_i(e, a_i) + a_i. \quad (34)$$

Proposition 6 *Denote the equilibrium of the Nash game with payoff functions $\pi_i = B_i - D_i - a_i, i = 1,$ and the extended damage functions D_i with the convexity properties Eq. (10) and Eq. (11) by $(e_1^\bullet, a_1^\bullet, e_2^\bullet, a_2^\bullet)$. Let $(\tilde{e}_1^\bullet, \tilde{e}_2^\bullet)$ be the equilibrium of the Nash game with payoff functions $\tilde{\pi}_i = B_i - \tilde{D}_i, i = 1, 2$, where $\tilde{D}_i$ are the optimized damage functions that are defined from the extended damage functions by Eq. (34). Then $\tilde{D}_i'' = \nu_i$ as defined by Eq. (17), $\tilde{e}_1^\bullet = e_1^\bullet$ and $\tilde{e}_2^\bullet = e_2^\bullet$.*

Proof 6 *By using the optimal adaptation decision function $A_i(e)$ that is given from the solution to $\partial_{a_i} D_i(e, A_i(e)) \equiv -1$, and exploiting Eq. (15) the optimized damage function can be written as*

$$\tilde{D}_i(e) = \min_{a_i} D_i(e, a_i) + a_i = D_i(e, A_i(e)) + A_i(e),$$

and thus

$$\tilde{D}_i'(e) = \partial_e D_i + \partial_{a_i} D_i A_i' + A_i' = \partial_e D_i(e, A_i(e)). \quad (35)$$

As $(\partial_{a_i} D_i + 1) A_i' = 0$, the marginal optimized damage is the same as the marginal basic damage. It follows that by using the the optimized damage functions $\tilde{D}_i$, the Nash equilibrium with extended damage functions D_i can equivalently described in terms of the optimized damage functions by

$$\forall i : D_i' = B_i'. \quad (36)$$

This is the same condition as for the Nash equilibrium in the standard case without adaptation Eq. (3). The solution of both games is identical.

Eq. (35) further implies that

$$\tilde{D}_i'' = \partial_{ee} \tilde{D}_i + \partial_{ea_i} \tilde{D}_i A_i'.$$

Substituing Eq. (20) and comparing with Eq. (17) then yields

$$\tilde{D}_i'' = \nu_i.$$

This proposition again underpins a strategic insignificance of adaptation in the Nash setting. The equivalence of the marginal optimized damage and the marginal basic damage is basically rooted in a duality argument as also put forward by (cf. Tulkens and van Steenberghe, 2009).

More importantly, it shows that β countries (with negative ν_i) have a concave optimized damage functions. This contrasts the standard case in the environmental economics literature, where the damage function is convex (corresponding to α-type countries with $\nu_i > 0$ in this paper). Although the extended damage function was generally assumed to be strictly convex in both arguments (jointly), this convexity does not necessarily carry over to the optimized damage function. This does not, however, invalidate the existence of a game equilibrium due to the convexity assumption Eq. (11). For β countries, both benefits and optimized damages are concave in the amount of emissions, but the curvature of the benefits is small enough to still guarantee the existence of optima. So, the positive result Prop. 3 shows that the game of timing leads to Pareto-improving unilateral action when one country has a concave optimized damage.

6 Conclusions

This paper has analyzed whether the option of adaptation – in addition to mitigation – improves the prospects of unilateral action in international emission games. Our model depicts unilateral action as a Stackelberg game and assumes a quite general class of *extended* damage functions. These fall into two types. The more conventional α-type is associated with a convex *optimized* damage function and with leakage in the case of unilateral emission reductions. Yet, when β-type countries are Stackelberg followers, unilateral action results in a reduction of total emissons and Pareto improvements for both countries.

This raises the question whether β-type countries would indeed be the followers. This is investigated in a game of timing at a stage before the emission and adaptation decisions. This determines the role of the leader and follower. The result is a positive one: a β-type country prefers to become the follower over a non-cooperative solution without unilateral action. There is thus a case for better prospects on international emission reductions when β-type countries exist and adpatation to damages is possible.

The results of this paper are theoretical in nature. We're not aware of empirical studies that indicate the existence of β countries for international pollution problems. Yet, in the field of climate change, the empirical base for damage functions is still very weak. The state of the art in modelling those is still strongly evolving (e.g. Tol, 2005; Watkiss, 2011). So it might currently be difficult to answer the empirical relevance of β countries robustly. It is yet interesting to observe that some damage functions used in the literature on the integrated assessment of climate change (cf. Nordhaus, 1993; Nordhaus and Boyer, 2000; Warren et al., 2006; Ortiz et al., 2011) are concave in parts of their domain. We suspect that this does not lead to problems with these models as their computed equilibria are (accidentally?) in the convex parts of their damage functions. In general, however, concave domains of damage functions are not implausible. As, for example, the general arguments of (Baumol, 1972) suggest, marginal damages may begin to decrease when damages come close the maximum that can be lost at all. In this interpretation, β countries would be those that either have a low damage potential, or those that suffer very high damages when emissions at the non-cooperative Nash level.

The current analysis focuses on the case with two countries. It would be interstng to extend the analysis to the N country case, such that also matters of coalitions stability can be studied. Our results show potential to extend the classic literature on international environmenal aggreements by representing more heterogeneity of countries, in particular the two types defined and analysed in this paper. Results might depend on the type of aggregates of multiple α-type and β-type countries, and how the type of the aggregate might change when countries join or leave the leading coalition. Moreover, an intertemporal analysis would allow for a more broad consideration of the timing and indolence of adaptation and mitigation investments in the context of a stock pollutant. Yet, this paper already shows at least one new case for being more optimistic to solve international environmental problems.

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