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Investment and Adaptation as Commitment Devices in Climate Politics

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Abstract

It is well established that adaptation and technological investment in each case may serve as a commitment device in international climate politics. This paper for the first time analyzes the combined impact of these two strategic variables on global mitigation within a non-cooperative framework where countries either decide on mitigation before or after adaptation. By investment, which is assumed to be made in the first place due to its considerable lead time, countries commit to lower national contributions to the global public good of mitigation. We find that the sequencing of adaptation before mitigation reinforces this strategic effect of technological investments at least for sufficiently similar countries. As a consequence, the subgame-perfect equilibrium yields a globally lower level of mitigation and higher global costs of climate change when adaptation is decided before mitigation. Besides this theoretical contribution, the paper proposes some strategies to combat the unfortunate rush to adaptation which can be currently observed in climate politics.

JEL classification: Q54, H41, H87, C72

Keywords: adaptation, climate policy, investment, mitigation, non-cooperative behavior

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1 Motivation

Following the setback of international mitigation efforts after the Copenhagen conference of the parties (COP15), adaptation to climate change has gained increasing attention in UNFCCC negotiations. The COP17 in Durban launched the Green Climate Fund (GCF) with an explicit stipulation of a balanced allocation of resources for adaptation and mitigation activities (UNFCCC 2013). Many developing countries involved in the GCF view such allocation to imply a share of funding for adaptation of at least fifty percent with a variation of not more than 10 percentage points (UNFCCC 2011). At the same time, many developed countries kick-started adaptation strategies at the national (Biesbroek et al. 2010) and local level (Kent 2012). The 'taboo on adaptation' (Pielke et al. 2007) of the 1990s climate negotiations has since been lifted (The Economist 2008). In fact, according to Berg (2012), adaptation rushes to overtake mitigation in many current statements on the future of climate politics. One reason for this shift of attitude is that adaptation is frequently seen as a low-cost option compared to mitigation. Indeed, the German 'Energiewende' highlights the immense infrastructural cost of cutting carbon emissions through the expansion of renewable energy (The Economist 2012). This lends strong evidence to Yohe's early finding on the importance of a 'mitigative capacity' to mirror the 'adaptive capacity' needed for effective adaptation (Yohe 2001).

The strategic implications of this prioritization of adaptation efforts for international climate policy have been neglected in much of the literature. Zehaie (2009) is one of the rare exceptions. He demonstrated that the sequencing of adaptation before mitigation has a detrimental effect on the outcome of international negotiations, since countries use domestic adaptation strategically to channel mitigation efforts to foreign countries. Contrary to Zehaie, who focuses on a 'semi-cooperative' approach, i.e. mitigation is decided under cooperation while adaptation as 'self-protection' is chosen non-cooperatively, the present paper departs from the finding that international negotiations on climate change under the roof of the UNFCCC do not go far beyond 'business as usual' (Böhringer and Vogt 2003 and 2004). In fact, we argue that the actual situation of climate change is reflected best by a purely non-cooperative setting and we confirm Zehaie's finding that the sequencing of adaptation before mitigation worsens the overall outcome of global mitigation.

Going beyond the model of Zehaie, we investigate the role of technological investment as a further decision variable in climate politics. The strategic importance of private investment in the context of international externalities has been analyzed from different perspectives (i.e. Buchholz and Konrad 1994, Stranlund 1996, Aggarwal and Narayan 2004). In the case of climate change, the main finding is that countries may strategically decrease their level of investment in order to shift the burden of mitigation to other countries (Buchholz and Konrad 1994). In other words, technological investment may serve as a commitment device in the same way as advancing adaptation does.

However, the concurrence of these two strategic effects and its joint impact on mitigation has not yet been analyzed. Since both strategic actions, i.e. increased adaptation and technological underinvestment, aim at committing to a lower effort in mitigation, two general outcomes are conceivable a priori: First, the strategic effects might substitute each other, i.e. a second strategic variable would not alter the level of mitigation in addition. In such a case, the sequencing of adaptation and mitigation would be irrelevant to the outcome since strategic technological underinvestment would induce the same low effort in mitigation anyway. Second, both strategic effects might support each other, thus resulting in a further deterioration of mitigation activities. According to this scenario, advancing adaptation would still be a relevant strategic factor in the countries' decisions on climate policy.

In our analysis, we demonstrate for sufficiently similar countries that both strategic effects in fact add up. Considering the choice of technological investment, the global level of mitigation is lower when adaptation is advanced. Such a deterioration in mitigation yields higher total costs at the global level. Consequently, the sequencing of adaptation in relation to mitigation is a crucial factor in climate politics in combination with other commitment devices. Our main conclusion from this result is that a more cautious approach on adaptation in climate politics could be superior to the current 'rush to adaptation'. The principle of a 'balanced strategy of mitigation and adaptation' will be needed to avoid the exacerbation of underinvestment in mitigation due to strategic behavior.

The paper is organized as follows. In Section 2, we describe the economic framework, present the basic model and define the efficiency benchmark. Moreover, the sequencing of adaptation, mitigation and investment is discussed. In Section 3, the subgame-perfect equilibria with regard to mitigation and adaptation are determined and the consequences of sequencing on total costs are analyzed. Section 4 allows for the decision on private technological investment and investigates its impact on the overall outcome, whereas the cases of sequencing adaptation before and after mitigation are compared. Finally, Section 5 proposes some strategies to combat the unfortunate 'rush to adaptation' that can be currently observed in climate politics. A short conclusion follows.

2 Economic Framework

We regard a static model of climate change in a two-country setting following the existing literature (see e.g. Zehaie 2009, Buob and Stephan 2011 or Ebert and Welsch 2012). Each country (home and foreign) can reduce its incurred damage costs of climate change by two strategies: mitigation M and adaptation A. Mitigation has the characteristics of a public good as it decreases *global* damage costs, while adaptation primarily yields benefits at the national level and, thus, is modeled as a national private good. Unlike the preceding literature, in our model the countries have available a third strategy: By expenditures for technological investment I a country enhances its mitigative capacity; i.e. the costs of mitigation decrease. Total costs accruing from climate change for the home and the foreign country are given by

$$\begin{aligned} T(M,m,A,I) &= D(M+m,A)+A+C(M,I)+I \\ t(M,m,a,i) &= d(M+m,a)+a+c(m,i)+i. \end{aligned} \tag{1}$$

Capital (lowercase) letters denote functions and variables of the home (foreign) country. Home country's damage costs are expressed by $D(M+m,A)$, which is twice continuously differentiable and strictly convex. Damage costs are decreasing in (domestic and foreign) mitigation as well as in domestic adaptation with diminishing marginal returns, i.e. $(D_1,D_2)<0$; $(D_{11},D_{22})>0$.[1] Increasing mitigation entails a decrease of the marginal effectivity of adaptation and vice versa, i.e. $D_{12}>0$.[2] The costs of mitigation $C(M,I)$ are strictly convex, $C_1, C_{11}>0$, and crucially depend on technological investment I in the following way: costs of mitigation decrease in investment with diminishing marginal returns, i.e. $C_2 \leq 0$, and $C_{22}>0$. Moreover, increasing investment reduces marginal costs of mitigation, and increasing mitigation raises the effectiveness of investment, i.e. $C_{12}=C_{21}<0$.[3] With regard to adaptation costs, we take up the reasoning of Ebert and Welsch (2011), who model the *expenditures* of adaptation instead of adaptation in physical units due to the heterogeneity of measures that adaptation comprises. Therefore, adaptation costs are linear, and we implicitly assume that countries choose an optimal mix of adaptation measures (see Ebert and Welsch 2011).[4] Based on the same rationale, costs of investment are assumed to be linear as well. The foreign country's total

[1] The subscripts 1 (2) denote the partial derivatives of a function with respect to its first (second) argument, e.g. $D_1=\frac{\partial D}{\partial M}=\frac{\partial D}{\partial m}$ and $D_2=\frac{\partial D}{\partial A}$. Furthermore, since the damage function is assumed to be strictly convex, we have $D_{11}D_{22}-D_{12}^2>0$.

[2] Despite the debate on adaptation and mitigation being complements, we follow the predominant opinion in the literature of a substitutional relationship between adaptation and mitigation (see, e.g. Ingham et al. 2005, Lecocq and Shalizi 2007 as well as Pittel and Rübbelke 2013).

[3] Cf. Buchholz and Konrad (1994) for a similar reasoning. Furthermore, strict convexity implies $C_{11}C_{22}-C_{12}^2>0$, and the Inada conditions are assumed to hold: $\lim_{I\to 0} C_2=-\infty$, $\lim_{I\to\infty} C_2=0$.

[4] Adaptation costs may also depend on technological innovation, but the link between adaptation costs and technology is considerably weaker than between mitigation costs and technology as adaptation measures mainly involve the prevention or removal of losses stemming from climate change. Mitigation, however, inherently depends on the changeover from traditional to low carbon and energy-efficient technologies (see, e.g. Buchholz and Konrad 1994).

costs have analogous properties.

In the following analysis, we evaluate how the sequence of the decisions on adaptation, mitigation and investment affects the non-cooperative equilibrium where the efficient allocation serves as a benchmark.

2.1 Efficiency Benchmark

In order to achieve the globally efficient allocation, countries minimize aggregate costs $T(M, m, A, I) + t(M, m, a, i)$. As efficiency requires full control of all variables, the sequencing of the decisions on investment, mitigation, and adaptation is irrelevant to the outcome. Thus, the aggregate costs are minimized with respect to all six variables simultaneously. The corresponding first-order conditions are

$$\begin{aligned} I, i: &\quad 1 + C_2 = 0 = 1 + c_2 \\ A, a: &\quad 1 + D_2 = 0 = 1 + d_2 \\ M, m: &\quad C_1 + D_1 + d_1 = 0 = c_1 + d_1 + D_1. \end{aligned} \tag{2}$$

For investment and adaptation, the efficient allocation implies equating marginal costs and the corresponding marginal 'benefits', which both occur on a national level. Marginal benefits of investment are simply given by the related marginal decrease in mitigation costs. In case of adaptation, marginal benefits are expressed by the marginal reduction of damage costs. In contrast to these private strategies, mitigation as a public good yields global benefits. Therefore, in the efficient allocation, each country's marginal costs of mitigation are balanced against the sum of marginal damages (i.e. benefits) in both countries. The system of these six equations defines the globally efficient allocation $(M^*, m^*, A^*, a^*, I^*, i^*)$.

2.2 Sequencing

In contrast to the efficient solution, the chronological order of the countries' decisions affects the equilibrium levels of mitigation, adaptation and investment substantively. In order to analyze the effect of sequencing on the subgame-perfect equilibrium, we set up two different idealized sequential games.

Investment in mitigation infrastructure (e.g. power grids) naturally requires a considerable lead time to become effective. Therefore, we assume that countries necessarily take the decision on investment in the first stage. For adaptation and mitigation, however, there is no established sequencing. Although some authors argue that, naturally, mitigation is fixed before adaptation because of the long term effects of mitigation (Buob and Stephan 2011, Ebert and Welsch 2012), adaptation consists of numerous heterogeneous strategies and some of them can also be decided before mitigation. For instance, there is facilitative adaptation which enhances the adaptive capacity of the population (Tol 2005), or adaptation with characteristics of investment (Zehaie 2009) which both have to be fixed in the long term.[5] In general, depending on the type of adaptation, it can be fixed before, simultaneously with, or after mitigation. Furthermore, as everybody expects aggregate mitigation efforts to fall short of the IPCC claims, the focus will turn to adaptation in advance. Therefore, we regard all possible sequences of adaptation and mitigation to be relevant. However, we refrain from considering the case of a simultaneous choice of adaptation and mitigation, since this can be reproduced by the sequential game of deciding on mitigation before adaptation (Zehaie 2009).[6] Hence, we solely investigate the two sequences depicted in Table 1, 'adaptation before mitigation' and 'mitigation before adaptation'.

sequencing	stage 1	stage 2	stage 3
'mitigation before adaptation'	investment	mitigation	adaptation
'adaptation before mitigation'	investment	adaptation	mitigation

Table 1: Sequencing of adaptation, mitigation and investment

3 Adaptation and Mitigation

In this section, we analyze the subgame-perfect equilibria for either sequence by applying backward induction. We first solve the last two stages disregarding the choice of investment and compare the equilibria to the efficient solution. The decision on investment in the first stage of the game and its impact on mitigation and adaptation in the subgame-perfect equilibria follows in Section 4.

3.1 Mitigation before Adaptation

At first, we analyze the case when mitigation is fixed before adaptation. In the third stage, both countries minimize their total costs with respect to A and a, respectively. This yields the first-order conditions

$$1 + D_2 = 0 = 1 + d_2, \tag{3}$$

which are identical to those of the efficient allocation. The optimal choices on adaptation are independent of the other country's decision. Thus, both countries have dominant strategies given the levels of aggregate mitigation fixed in the second stage, i.e. $A(M + m)$ and $a(M + m)$.

In stage 2, countries decide simultaneously on mitigation while anticipating the levels of adaptation chosen in stage 3. Minimizing $T(M, m, A(M + m), I)$ with

[5] Auerswald et al. (2011) also consider the case of adaptation being fixed before mitigation when analyzing the impact of risk preferences on climate policy.

[6] However, this equivalence may not hold if climate funding is regarded (see Heuson et al. 2013).

respect to M yields the following first-order condition

$$C_1 + D_1 + \underbrace{[1 + D_2]}_{=0 \text{ eq.(3)}} \cdot \frac{\partial A}{\partial M} = 0 \tag{4}$$

for the home country. The analogous condition characterizes the optimal choice in the foreign country. According to (4), countries choose the level of mitigation at which marginal costs equal *national* marginal benefits only. Contrary to the efficiency benchmark, the positive externality of mitigation on the damage of the neighboring country is not considered in the non-cooperative case. The countries' mitigation efforts are strategic substitutes since it can be shown by the implicit function theorem that $-1 < \frac{\partial M}{\partial m} = -\frac{D_{11}D_{22} - D_{12}^2}{D_{22}C_{11} + D_{11}D_{22} - D_{12}^2} < 0$.[7]

3.2 Adaptation before Mitigation

Second, we analyze the sequential game with adaptation being fixed before mitigation. In the third stage, countries decide on mitigation which yields the following first-order conditions for home and foreign

$$C_1 + D_1 = 0 = c_1 + d_1. \tag{5}$$

These conditions can be explained analogously to (4). Again, mitigation of home and foreign are strategic substitutes.[8] The equilibrium level of mitigation also depends on adaptation and investment.

In stage 2, the countries minimize total costs with respect to their levels of adaptation. Considering the equilibrium in stage 3, the following first-order condition arises for home

$$1 + D_2 + \underbrace{[C_1 + D_1]}_{=0 \text{ eq.(5)}} \cdot \frac{\partial M}{\partial A} + D_1 \cdot \frac{\partial m}{\partial A} = 0. \tag{6}$$

In contrast to the efficiency benchmark (2), a strategic effect occurs which is represented by the last term of (6). This term is negative, as $D_1 < 0$ and $\frac{\partial m}{\partial A} > 0$ (see Appendix 1), and reflects the additional marginal benefits of adaptation which arise when adaptation is fixed before mitigation. Since domestic mitigation and adaptation are substitutes, by increasing adaptation the home country commits to a lower level of mitigation in the following stage. The foreign country anticipates the lower level of domestic mitigation and, in response, elevates its effort in mitigation since domestic and foreign mitigation are strategic substitutes. The home country

[7] This relation holds due to convexity of the damage function D.

[8] However, strategic substitutability changes with sequencing in the sense that $-1 < \frac{dM}{dm} = -\frac{D_{11}}{C_{11}+D_{11}} < 0$. The best response when mitigation is chosen before adaptation is not as elastic as for the opposite sequencing.

benefits from this response because foreign mitigation reduces the domestic damage.

Consequently, adaptation in stage 2 serves as a commitment device to a lower mitigation effort and induces an increase in foreign mitigation in stage 3. However, the global level of mitigation decreases with adaptation as the (direct) effect on the level of domestic mitigation outweighs the (indirect) one on foreign mitigation: $\frac{\partial[M+m]}{\partial A} < 0$.[9] The analogous first-order condition and reasoning hold for the foreign country.

3.3 Consequences of Advancing Adaptation

Disregarding the choice of investment, we compare the non-cooperative equilibria in stage 2 and 3. The system of (3) and (4) yields the subgame-perfect equilibrium $(A^\circ, a^\circ, M^\circ, m^\circ)$ where mitigation is chosen before adaptation. For the reverse sequencing, the system of (5) and (6) yields the subgame-perfect levels $(A^\triangle, a^\triangle, M^\triangle, m^\triangle)$, where adaptation increases due to the strategic effect described in the previous section. To simplify the analysis, we assume in what follows that $\frac{\partial m}{\partial A}$ and $\frac{\partial M}{\partial a}$ are approximately constant and, thus, independent of mitigation and adaptation itself.[10]

Comparing the two subgame-perfect equilibria gives rise to

Proposition 1 *Consequences of advancing adaptation.*
i) When the decision on adaptation is advanced, the home and the foreign country strategically raise their respective levels of adaptation compared to the reverse sequencing, $(A^\triangle, a^\triangle) > (A^\circ, a^\circ)$.
ii) Due to this increase in adaptation, the global contribution to mitigation in the subgame-perfect equilibrium where adaptation is chosen before mitigation is lower than in the opposite sequence: $(M^\triangle + m^\triangle) < (M^\circ + m^\circ)$.

Proof. See Appendix 2. ■

We can explain this result by the following intuition. Comparing the first-order conditions regarding adaptation in the non-cooperative cases, (3) and (6), it can be found that additional benefits of adaptation arise when it is chosen before mitigation. As marginal costs of adaptation remain unchanged, each country chooses a higher level of adaptation compared to the opposite sequencing. Regarding mitigation, the first-order conditions, (4) and (5), are identical. Strategic increases in adaptation in home *and* foreign have opposing effects on the respective levels of mitigation. On the one hand, a higher level of domestic adaptation induces a decrease in marginal

[9] See Appendix 1 and cf. Zehaie (2009) for a similar result.

[10] To be precise, this requires the third-order derivatives of $C(\cdot)$ and $D(\cdot)$ to be sufficiently small or ideally zero which will be true for (quadratic) polynomial costs of degree two. In case of arbitrary cost functions we then apply their second-order Taylor approximation.

benefit of domestic mitigation. On the other hand, an opposing indirect effect arises due to the increase in adaptation and the involved decrease in mitigation in the neighboring country. For sufficiently similar countries, the direct effect always outweighs the indirect one. However, in the case of highly asymmetric countries, the partial compensation of the decrease in mitigation through the neighboring country might outweigh the direct effect. Therefore, the levels of mitigation do not necessarily decline in *both* countries due to advancing adaptation. However, the *global* level of mitigation is definitely lower when adaptation is fixed first since crowding out is just partial.[11]

Next, let us consider the consequences of the different sequences on global costs. We start by comparing the non-cooperative equilibrium without any strategic effects to the efficiency benchmark (M^*, m^*, A^*, a^*). This gives rise to

Proposition 2 *Underprovision of mitigation as a public good.*
In the subgame-perfect equilibrium where mitigation is fixed before adaptation, the global level of mitigation is inefficiently low: $(M^\circ + m^\circ) < (M^* + m^*)$.

Proof. Domestic mitigation decreases the foreign country's total costs and vice versa, i.e. $\left(\frac{\partial t}{\partial M}, \frac{\partial T}{\partial m}\right) < 0$. As this positive externality of mitigation is not considered in the subgame-perfect equilibrium, mitigation is inefficiently low. ■

Proposition 3 *Adaptation as a substitute for mitigation.*
In the subgame-perfect equilibrium where mitigation is fixed before adaptation, the level of adaptation exceeds that of the efficient allocation: $(A^\circ, a^\circ) > (A^*, a^*)$.

Proof. For both, the efficient solution and the subgame-perfect equilibrium where mitigation is fixed first, the best choice of adaptation is characterized by identical first-order conditions (2) and (3). As mitigation in the subgame-perfect equilibrium is lower than in the efficient allocation, the marginal benefit of adaptation is comparatively higher in the non-cooperative case. Since marginal costs of adaptation remain unchanged, the subgame-perfect level of adaptation must exceed the efficient level. ■

Corollary 1 *Global ranking of the subgame-perfect equilibria.*
The subgame-perfect equilibrium where mitigation is fixed before adaptation yields a globally superior result relative to the subgame-perfect equilibrium where adaptation is chosen before mitigation:
$(M^* + m^*) > (M^\circ + m^\circ) > (M^\triangle + m^\triangle)$ *and* $(A^*, a^*) < (A^\circ, a^\circ) < (A^\triangle, a^\triangle)$.

[11] See Appendix 2 for the formal analysis of these results.

Proof. Follows directly from Propositions 1-3. ■

When adaptation is fixed before mitigation, each country uses adaptation as a commitment device in order to incentivize the neighboring country to increase its contribution to the public good of mitigation. In other words, each country tries to improve its national situation at the expense of its neighbor. However, in sum, the possibility of strategic adaptation yields a globally lower level of mitigation as the decline in domestic mitigation is greater than the reverse indirect effect on the neighbor country's mitigation. Consequently, the subgame-perfect equilibrium when adaptation is fixed before mitigation is globally inferior to the opposite sequence of decisions. If countries are sufficiently similar, a global decrease in mitigation implies that the effort in mitigation of each country declines. As a consequence, both countries definitely fall short of achieving their strategic aim to improve the own situation on expense of the other country. Hence, the case of advancing adaptation yields a Pareto-inferior result for sufficiently similar countries.

Our results show that the currently ongoing political prioritization of adaptation is globally counterproductive. Due to the ensuing strategic increase in adaptation, the global level of mitigation, which is already inefficiently low, suffers from an additional downgrade. Therefore, the problem of the underprovision of the global public good of mitigation impends to get worse.

4 Investment

In this section, we focus on the investment decision in the first stage and its consequences on the subgame-perfect equilibria. In particular, we consider the question of whether the strategic choice on investment will support or countervail the strategic effect of advancing adaptation which was analyzed in Section 3.

4.1 Mitigation before adaptation

Anticipating stages 2 and 3, the home country minimizes total costs with respect to I. This yields the following first-order condition for home (and analogously for foreign)

$$C_2 + 1 + \underbrace{[1 + D_2]}_{=0 \text{ eq. (3)}} \cdot \frac{\partial A}{\partial I} + \underbrace{[C_1 + D_1]}_{=0 \text{ eq. (4)}} \cdot \frac{\partial M}{\partial I} + D_1 \cdot \frac{\partial m}{\partial I} = 0. \tag{7}$$

In comparison to the efficiency benchmark (2), there arises a strategic effect which is represented by the last term in (7). This effect is positive since $\frac{\partial m}{\partial I} < 0$ (see Appendix 3). Consequently, additional marginal costs of investment arise while marginal benefits remain unchanged, and the home country strategically lowers its level of investment. This can be explained as follows: As investment and mitigation are complements in the sense of $\frac{\partial M}{\partial I} > 0$, lower investment serves as a device for committing to a lower level of domestic mitigation. As domestic and foreign mitigation are strategic substitutes, the foreign country increases its level of mitigation in the second stage and the home country benefits. However, the net effect of a decline in investment on the global level of mitigation is negative since $\frac{\partial [M+m]}{\partial I} = -C_{12} \cdot c_{11} / \det_2 > 0$ (see Appendix 3).

4.2 Adaptation before mitigation

In case adaptation is fixed before mitigation, the home country's first order condition with respect to I reads

$$C_2 + 1 + \underbrace{\left[1 + D_2 + D_1 \frac{\partial m}{\partial A}\right]}_{=0 \text{ eq. (6)}} \cdot \frac{\partial A}{\partial I} + \underbrace{[C_1 + D_1]}_{=0 \text{ eq. (5)}} \cdot \frac{\partial M}{\partial I} + D_1 \cdot \frac{\partial m}{\partial I} = 0. \tag{8}$$

This condition is similar to (7), and therefore, the reasoning is analogous: Investment serves as a commitment device to a lower level of mitigation which in turn raises the foreign mitigation effort. Again, mitigation in the home and the foreign country are strategic substitutes and the overall effect of a decline in investment on the global level of mitigation is negative as $\frac{\partial [M+m]}{\partial I} > 0$ (see Appendix 3). The analogous first-order condition and reasoning hold for the foreign country.

4.3 Subgame-Perfect Equilibria with Investment

Eqs. (3), (4) and (7) determine the equilibrium $(M^\circ, m^\circ, A^\circ, a^\circ, I^\circ, i^\circ)$ in which mitigation is chosen before adaptation, whereas the equilibrium $(M^\triangle, m^\triangle, A^\triangle, a^\triangle, I^\triangle, i^\triangle)$ with adaptation before mitigation is defined by (5), (6) and (8). Comparing these subgame-perfect equilibria with the efficient allocation $(M^*, m^*, A^*, a^*, I^*, i^*)$ gives rise to

Proposition 4 *Reduced mitigation effort due to underinvestment in technology. Independently of the sequential choice of mitigation and adaptation, countries underinvest in technology relative to the efficient solution, i.e.* (I°, i°), $(I^\triangle, i^\triangle) < (I^*, i^*)$. *This strategic underinvestment induces a globally lower level of mitigation in each subgame-perfect equilibrium compared to the efficient allocation, i.e.* $(M^\circ + m^\circ), (M^\triangle + m^\triangle) < (M^* + m^*)$.

Proof. We compare the first-order conditions with regard to investment, (7) and (8), to the efficient solution (2). Due to the strategic effect in terms of investment in (7) and (8), marginal benefits of investment decrease and countries choose a lower level of investment compared to the efficiency benchmark, i.e. both (I°, i°) and $(I^\triangle, i^\triangle)$

fall short of (I^*, i^*). In the subsequent stages, lower levels of investment induce higher marginal costs of mitigation. Moreover, in accordance with Proposition 2 and Corollary 1, the positive externality of mitigation is not considered in the non-cooperative cases. Thus, for the first-order conditions with regard to mitigation, (4) and (5), to hold, the global levels of mitigation in the subgame-perfect equilibria must be lower in comparison with the efficient allocation, i.e. $(M^\circ + m^\circ), (M^\triangle + m^\triangle) < (M^* + m^*)$. ■

Independent of the sequence of mitigation and adaptation, strategic underinvestment in the first stage serves as a commitment device to a lower level of mitigation for both countries.[12] With respect to sequencing, we observe the following results.

Proposition 5 *Sequencing of adaptation before mitigation remains globally inferior.*
For sufficiently similar (i.e. symmetric and slightly asymmetric) countries, the subgame-perfect equilibrium depends on sequencing in the following way.
i) When adaptation is advanced, both the level of investment and mitigation are reduced; i.e. $I^\triangle < I^\circ$ *and* $M^\triangle < M^\circ$. *This is accompanied by an increase in adaptation* $A^\triangle > A^\circ$.
ii) The choice of adaptation before mitigation is globally inferior; i.e. $M^\triangle < M^\circ < M^*$.

Proof. See Appendix 4 for part i), part ii) is obvious. ■

Provided that countries are sufficiently similar, the levels of investment are lower when adaptation is advanced, i.e. the magnitude of underinvestment is intensified. Consequently, the global level of mitigation is lower, and, in accordance with Corollary 1, the resulting subgame-perfect equilibrium for sufficiently similar countries with adaptation being fixed before mitigation remains globally inferior to the reverse sequencing.[13] Intuitively, this result can be explained by the effect of strategic adaptation, which causes a lower level of mitigation. Due to this lower 'demand' for mitigation, marginal benefits of technological investments decrease, and less investments are made in the subgame-perfect equilibrium where adaptation is fixed before mitigation.

Therefore, accounting for up-front investment decisions confirms the result of Section 3.3 for sufficiently similar countries. Promoting early action in adaptation increases the global costs stemming from climate change. Efficiency suffers from adaptive measures in advance.

[12] Following Ulph (1996), we assume that - within any one-shot game - investment in technology is irreversible and thus allows for credibly committing to specific behaviors (here: mitigation effort) that are affected by the investment in subsequent stages.

[13] The impact of sequencing on investments for highly asymmetric countries, however, cannot be determined unambiguously.

5 Policies to Combat Strategic Incentives in Sequencing

The chronological order to decide on mitigation versus adaptation does not follow a 'natural logic' much in contrast to investment, which has to be taken prior to actions of mitigation to enhance the capabilities to engage in climate protection. In the early period of climate change negotiations advancing Copenhagen's COP15, the order was fixed in a silent international consensus as 'mitigation before adaptation' which was labeled the 'taboo on adaptation' (Pielke 2007). This has since been lifted and due to the missing progress in combating climate change, the political focus seems to shift towards 'adaptation before mitigation'. Accordingly, developed countries have currently elaborated detailed plans of adaptation to climate change (e.g. European Commission 2013, ICCATF 2011) and the UNFCCC national adaptation programmes of action (NAPAs) provide funding for the urgent needs of adaptation for least developed countries (UNFCCC 2007). These plans on adaptation provide important information to improve climate change resilience, but they might reverse the 'unspoken order' of decisions of adaptation and mitigation. In this paper, we have demonstrated that the order of 'mitigation before adaptation' is strictly preferable in a non-cooperative international context. In as much as the hidden agenda of Kyoto could be reinstalled, i.e. adaptation decisions could be postponed to a period after mitigation has been decided, we should do so in order to avoid aggravating strategic decision-making and globally higher costs. However, this will be difficult in practice as there is no open agenda process on mitigation versus adaptation. The previous 'taboo on adaptation' was more an emotional mind-set of negotiators in the past than a principle enshrined into the UNFCCC.

There are several ways to combat the undesirable consequences of sequencing adaptation before mitigation, which each in itself does not resolve the problem of strategic incentives but may contribute to control it. They would each need some kind of implicit collaboration of countries in form of funding which goes beyond the framework of non-cooperation assumed in this paper. However, since funding under Post-Kyoto framework has been agreed independently of targets of adaptation and mitigation – specifically the fast track finance after the Cancun agreement (2010-2012) – we could consider non-cooperation in terms of mitigation and adaptation combined with implicit cooperation in terms of funding. As demonstrated theoretically by Heuson et al. (2013), several instruments of climate funding could yield Pareto-improvements for donor and recipient countries. Consequently, funding might induce an implicit cooperation. The green climate funding is currently the single most progressing agenda item of UNFCCC to structure an implicit order of decision making on mitigation and adaptation. The Cancun agreement on the

Green Climate Fund in particular urges decisions on adaptation and decisions on mitigation to be taken simultaneously. Such a parallel funding would prevent to focus on adaptation only. Furthermore, when climate funding is subject to a 'balanced allocation' provision such as the GCF, it will set an upper bound for strategic underinvestment in mitigation. Similarly, technology funds which are directed towards mitigation in developing countries such as the Clean Technology Fund of the World Bank (e.g. CIF 2103 and World Bank 2008), or Green Stimulus Programs (cf. Barbier 2010) which enhance investments in low carbon development in developed countries or emerging markets' countries are potential means to guide us into the right direction to avoid the unfortunate current 'rush to adaptation'.

6 Conclusion

In recent years, adaptation to climate change has gained increasing attention both at the national and international level. For example, national adaptation strategies have been elaborated and diverse international adaptation funds have been launched. These developments demonstrate that the decision of adaptation is likely to be advanced on the political agenda. In the present paper, we investigate the economic consequences of this current shift in priority from mitigation to adaptation.

When adaptation is chosen before mitigation, countries strategically intensify their expenditures on adaptation in order to shift some costs of mitigation to the neighboring country. From a unilateral perspective, this strategic behavior might improve the economic situation of a country (see Zehaie 2009, BMF 2010 and Auerswald et al. 2011). However, the global level of mitigation effectively declines.

This paper further analyzes the subgame-perfect equilibria where mitigation is chosen before and after adaptation, respectively, in comparison to the efficiency benchmark. Advancing the decision on adaptation in both countries yields a globally inferior subgame-perfect allocation relative to the case when mitigation is fixed before adaptation. In other words, global costs of climate change rise if the decision on adaptation is advanced.

In a second step, we investigate the role of investment in technology which is essential for a country's mitigative capacity. As the German 'Energiewende' illustrates, immense investments in infrastructure are necessary for the transmission to a low-carbon energy supply. The considerable lead time of investment requires that this decision is taken in advance of both mitigation and adaptation, and, therefore, investment serves as a commitment device in order to shift the burden of mitigation to the neighboring country. Comparing the resulting subgame-perfect equilibria to the efficiency benchmark, two main conclusions arise: First, due to strategic underinvestment, the global level of mitigation decreases in either case of sequencing.

Consequently, in case of upfront investment, the problem of underprovision of mitigation becomes even more serious. Second, it can be shown for sufficiently similar countries that the level of investment in the subgame-perfect equilibrium is even lower when adaptation is taken in advance than in case of the opposite sequencing. Thus, regarding investment, the negative effect of advancing adaptation on global mitigation is even intensified – and global costs of climate change increase further.

In sum, the current shift of attention towards adaptation in national and international climate policies reinforces the problem of the voluntary provision of mitigation from an economic point of view. Therefore, we suggest to keep the political focus on enhancing mitigation, or at least bind the progress on adaptation on parallel efforts in mitigation in the framework of a 'balanced strategy'. As investment naturally must be taken in advance, this sequence cannot be influenced politically. Nevertheless, it might be useful to strengthen the role of technology funds or Green Stimulus Programs.

Appendix 1: Comparative statics for adaptation and mitigation

In case adaptation is chosen before mitigation, the impact adaptation has on mitigation in the third stage can be determined by differentiating the first-order conditions of mitigation in home and foreign with respect to adaptation[14]

$$\begin{pmatrix} dM \\ dm \end{pmatrix} = -\frac{1}{\det_1} \begin{pmatrix} [c_{11}+d_{11}]\,D_{12} & -D_{11}d_{12} \\ -d_{11}D_{12} & [C_{11}+D_{11}]\,d_{12} \end{pmatrix} \begin{pmatrix} dA \\ da \end{pmatrix}. \tag{A.1}$$

From (A.1) it can be seen that domestic adaptation has a negative (positive) impact on domestic (foreign) mitigation, $\frac{\partial M}{\partial A} = -[c_{11}+d_{11}] \cdot D_{12}/\det_1 < 0$ and $\frac{\partial m}{\partial A} = d_{11} \cdot D_{12}/\det_1 > 0$. However, as $\frac{\partial [M+m]}{\partial A} = -c_{11} \cdot D_{12}/\det_1 < 0$ the overall effect of adaptation on global mitigation is negative. The impact of foreign adaptation is analogous.

Appendix 2: Sequencing of adaptation and mitigation

In order to determine the impact the sequencing of adaptation and mitigation has on the subgame-perfect equilibria in stage 2 (including stage 3), we have to analyze the comparative statics of the choices on (M, m, A, a). The first-order conditions with respect to mitigation, (4) and (5), are identical in either case of sequencing, but the optimal choices on adaptation, (3) and (6) differ with respect to the strategic term. However, we can integrate both in a single approach such that the first-order conditions for home and foreign, respectively, are given by

$$1 + D_2 + \delta D_1 \frac{\partial m}{\partial A} = 0 \tag{A.2}$$

$$1 + d_2 + \delta d_1 \frac{\partial M}{\partial a} = 0. \tag{A.3}$$

Here, the parameter δ serves to distinguish the different cases of sequencing on adaptation and mitigation. If mitigation is chosen before adaptation, we have $\delta = 0$, and in the opposite case $\delta = 1$. For convenience we have assumed that $\frac{\partial m}{\partial A}$ and $\frac{\partial M}{\partial a}$ are approximately constant and, thus, independent of mitigation and adaptation itself.

Proof for part *i*) of Proposition 1: In order to analyze the impact of sequencing, we totally differentiate the first-order conditions (A.2) and (A.3) of the decisions on adaptation regarding δ

[14] The determinant $\det_1 = [c_{11}+d_{11}][C_{11}+D_{11}] - d_{11}D_{11}$ is always positive. Thus, the Nash equilibrium at that stage is stable and unique, cf. Tirole (1988, p. 324).

$$\begin{pmatrix} D_{22}+\delta D_{12}\frac{\partial m}{\partial A} & 0 \\ 0 & d_{22}+\delta d_{12}\frac{\partial M}{\partial a} \end{pmatrix}\begin{pmatrix} dA \\ da \end{pmatrix}+$$

$$\begin{pmatrix} D_{12}+\delta D_{11}\frac{\partial m}{\partial A} & D_{12}+\delta D_{11}\frac{\partial m}{\partial A} \\ d_{12}+\delta d_{11}\frac{\partial M}{\partial a} & d_{12}+\delta d_{11}\frac{\partial M}{\partial a} \end{pmatrix}\begin{pmatrix} dM \\ dm \end{pmatrix} \tag{A.4}$$

$$= \; -\begin{pmatrix} D_1\frac{\partial m}{\partial A} \\ d_1\frac{\partial M}{\partial a} \end{pmatrix} d\delta.$$

Inserting (A.1) and rearranging terms yields

$$\begin{pmatrix} dA \\ da \end{pmatrix} = \frac{-\begin{pmatrix} \frac{\left[d_{22}+\delta d_{12}\frac{\partial M}{\partial a}\right]c_{11}\left[1+\frac{D_{11}}{C_{11}}\right]+d_{11}d_{22}-[d_{12}]^2}{c_{11}\left[1+\frac{D_{11}}{C_{11}}\right]+d_{11}} & \frac{\left[D_{12}+\delta D_{11}\frac{\partial m}{\partial A}\right]d_{12}}{c_{11}\left[1+\frac{D_{11}}{C_{11}}\right]+d_{11}} \\ \frac{\left[d_{12}+\delta d_{11}\frac{\partial M}{\partial a}\right]D_{12}}{C_{11}\left[1+\frac{d_{11}}{c_{11}}\right]+D_{11}} & \frac{\left[D_{22}+\delta D_{12}\frac{\partial m}{\partial A}\right]C_{11}\left[1+\frac{d_{11}}{c_{11}}\right]+D_{11}D_{22}-[D_{12}]^2}{C_{11}\left[1+\frac{d_{11}}{c_{11}}\right]+D_{11}} \end{pmatrix}}{\det_2} \tag{A.5}$$

$$\cdot \begin{pmatrix} D_1\frac{\partial m}{\partial A} \\ d_1\frac{\partial M}{\partial a} \end{pmatrix} d\delta.$$

All elements of the 2x2-matrix above are positive and both elements of the vector are negative. Furthermore, it can be shown (after some tedious math) that the appropriate determinant det_2 is positive as well. Hence, the levels of adaptation in home and foreign increase in δ, i.e. $\frac{\partial A}{\partial \delta} > 0$ and $\frac{\partial a}{\partial \delta} > 0$. Therefore, the equilibrium levels of adaptation are higher in each country when adaptation is chosen before mitigation, i.e. $A^{\Delta} > A^{\circ}$.

Proof for part *ii*) of Proposition 1: The first-order conditions with respect to mitigation, (4) and (5), are identical and do not directly depend on the sequencing of adaptation and mitigation (i.e. on δ). Thus, mitigation in home and foreign is just indirectly effected by sequencing, which can be represented by $\frac{\partial M}{\partial \delta} = \frac{\partial M}{\partial A}\frac{\partial A}{\partial \delta} + \frac{\partial M}{\partial a}\frac{\partial a}{\partial \delta}$ and, accordingly, $\frac{\partial m}{\partial \delta} = \frac{\partial m}{\partial A}\frac{\partial A}{\partial \delta} + \frac{\partial m}{\partial a}\frac{\partial a}{\partial \delta}$. Due to opposing effects of increasing adaptation in home and foreign on mitigation (see Appendix 1), the signs of $\frac{\partial M}{\partial \delta}$ and $\frac{\partial m}{\partial \delta}$ cannot be determined unambiguously for asymmetric countries. However, the overall impact of sequencing adaptation before mitigation yields a globally lower level of mitigation since $\frac{\partial [M+m]}{\partial \delta} = \frac{\partial [M+m]}{\partial A}\frac{\partial A}{\partial \delta} + \frac{\partial [M+m]}{\partial a}\frac{\partial a}{\partial \delta} < 0$ due to $\frac{\partial [M+m]}{\partial A}, \frac{\partial [M+m]}{\partial a} < 0$ (cf. Appendix 1). Thus, the total level of mitigation in equilibrium decreases with $\delta \in [0;1]$ such that $\left[M^{\Delta}+m^{\Delta}\right] < [M^{\circ}+m^{\circ}]$. Therefore, at least in one of the two countries the level of mitigation is lower when adaptation is advanced. Moreover, for symmetric countries it can be shown that $\frac{\partial M}{\partial \delta} = \frac{\partial m}{\partial \delta} = -\frac{C_{11} D_{12}}{\det_1} \frac{\partial A}{\partial \delta} < 0$, i.e. mitigation in both home and foreign is smaller when adaptation is advanced. As all best-response functions are continuous, the same result holds true even for slightly asymmetric countries.

Appendix 3: Comparative statics considering investment

We determine the strategic effect of investment on mitigation by comparative statics. Totally differentiating the first-order conditions of the decisions on mitigation of home and foreign, (4) and, respectively, (5), yields

$$\begin{pmatrix} C_{11} + D_{11} & D_{11} \\ d_{11} & c_{11} + d_{11} \end{pmatrix} \begin{pmatrix} dM \\ dm \end{pmatrix} + \begin{pmatrix} D_{12} & 0 \\ 0 & d_{12} \end{pmatrix} \begin{pmatrix} dA \\ da \end{pmatrix} = -\begin{pmatrix} C_{12} & 0 \\ 0 & c_{12} \end{pmatrix} \begin{pmatrix} dI \\ di \end{pmatrix}. \tag{A.6}$$

In order to substitute $(dA; da)$, we totally differentiate the first-order conditions of the decisions on adaptation, (3) and (6), for a given sequencing (i.e. $d\delta = 0$)

$$\begin{pmatrix} dA \\ da \end{pmatrix} = -\begin{pmatrix} \frac{\left[D_{12} + \delta D_{11} \frac{\partial m}{\partial A}\right]}{\left[D_{22} + \delta D_{12} \frac{\partial m}{\partial A}\right]} & \frac{\left[D_{12} + \delta D_{11} \frac{\partial m}{\partial A}\right]}{\left[D_{22} + \delta D_{12} \frac{\partial m}{\partial A}\right]} \\ \frac{\left[d_{12} + \delta d_{11} \frac{\partial M}{\partial a}\right]}{\left[d_{22} + \delta d_{12} \frac{\partial M}{\partial a}\right]} & \frac{\left[d_{12} + \delta d_{11} \frac{\partial M}{\partial a}\right]}{\left[d_{22} + \delta d_{12} \frac{\partial M}{\partial a}\right]} \end{pmatrix} \begin{pmatrix} dM \\ dm \end{pmatrix}, \tag{A.7}$$

which shows that adaptation is a substitute to mitigation independent of its origin and sequencing.

Substituting $(dA; da)$ from (A.7) in (A.6), rearranging terms and solving the equation system for the change in mitigation, yields

$$\begin{pmatrix} dM \\ dm \end{pmatrix} = \frac{-\begin{pmatrix} C_{12}\left[c_{11} + \frac{d_{11} d_{22} - [d_{12}]^2}{d_{22} + \delta d_{12} \frac{\partial M}{\partial a}}\right] & -\frac{c_{12}\left[D_{11} D_{22} - [D_{12}]^2\right]}{D_{22} + \delta D_{12} \frac{\partial m}{\partial A}} \\ -\frac{C_{12}\left[d_{11} d_{22} - [d_{12}]^2\right]}{d_{22} + \delta d_{12} \frac{\partial M}{\partial a}} & c_{12}\left[C_{11} + \frac{D_{11} D_{22} - [D_{12}]^2}{D_{22} + \delta D_{12} \frac{\partial m}{\partial A}}\right] \end{pmatrix} \begin{pmatrix} dI \\ di \end{pmatrix}}{\det_3}, \tag{A.8}$$

where determinant $\det_3 = \left[C_{11} + \frac{D_{11} D_{22} - D_{12}^2}{D_{22} + \delta D_{12} \frac{\partial m}{\partial A}}\right]\left[c_{11} + \frac{d_{11} d_{22} - d_{12}^2}{d_{22} + \delta d_{12} \frac{\partial M}{\partial a}}\right] - \left[\frac{D_{11} D_{22} - D_{12}^2}{D_{22} + \delta D_{12} \frac{\partial m}{\partial A}}\right]\left[\frac{d_{11} d_{22} - d_{12}^2}{d_{22} + \delta d_{12} \frac{\partial M}{\partial a}}\right] > 0$ is always positive such that the Nash equilibrium is again stable and unique (Tirole 1988).

Comparative statics show that domestic investment is a strategic complement (substitute) to domestic (foreign) mitigation, $\frac{\partial M}{\partial I} = -\frac{C_{12}}{\det_3}\left[c_{11} + \frac{d_{11} d_{22} - [d_{12}]^2}{d_{22} + \delta d_{12} \frac{\partial M}{\partial a}}\right] > 0$ and $\frac{\partial m}{\partial I} = \frac{C_{12}}{\det_3}\left[\frac{d_{11} d_{22} - [d_{12}]^2}{d_{22} + \delta d_{12} \frac{\partial M}{\partial a}}\right] < 0$. Moreover, investment encourages mitigation efforts globally $\frac{\partial(M+m)}{\partial I} = -C_{12} \cdot c_{11} / \det_3 > 0$. The first two relations directly follow from the convexity of the damage functions, i.e. $d_{11}d_{22} - [d_{12}]^2 > 0$. Furthermore, the denominators are positive irrespective of the sequential choice of adaptation and mitigation since $\frac{\partial M}{\partial a}, \frac{\partial m}{\partial A} > 0$ (see Appendix 1).

Appendix 4: Comparative statics and sequencing considering investment

To compare the effects of investment in the two different sequential games, we evaluate the subgame-perfect investment levels. In the symmetric case, three first-order conditions characterize the entire equilibrium which, in turn depends on sequencing δ

$$\begin{aligned} 1 + C_2(M, I) + D_1(2M; A) \cdot \tfrac{\partial m}{\partial I} &= 0 \\ C_1(M, I) + D_1(2M, A) &= 0 \\ 1 + D_2(2M, A) + \delta \cdot D_1(2M, A) \cdot \tfrac{\partial m}{\partial A} &= 0 \ . \end{aligned} \tag{A.9}$$

These three equations determine the subgame-perfect equilibrium in symmetric adaptation A, mitigation M and investment I, while δ enables us to distinguish between the different types of sequencing. For convenience we have assumed that $\frac{\partial m}{\partial I}$ and $\frac{\partial m}{\partial A}$ are approximately constant and, thus, independent of investments, mitigation, and adaptation itself. Totally differentiating (A.9) yields

$$\begin{pmatrix} \frac{dA}{d\delta} \\ \frac{dM}{d\delta} \\ \frac{dI}{d\delta} \end{pmatrix} = - \begin{pmatrix} D_{12}\frac{\partial m}{\partial I} & C_{21} + 2D_{11}\frac{\partial m}{\partial I} & C_{22} \\ D_{12} & C_{11} + 2D_{11} & C_{12} \\ D_{22} + \delta D_{12}\frac{\partial m}{\partial A} & 2\left[D_{21} + \delta D_{11}\frac{\partial m}{\partial A}\right] & 0 \end{pmatrix}^{-1} \begin{pmatrix} 0 \\ 0 \\ D_1\frac{\partial m}{\partial A} \end{pmatrix} . \tag{A.10}$$

Thus, the elements of the cofactor matrix corresponding to (A.10) determine the signs of the comparative statics[15]

[15] Cf. Sydsaeter et al. (2005, 4f). For a stable equilibrium the determinant of the matrix in (A.10) is positive.

$$\text{sign}\begin{pmatrix} \frac{dA}{d\delta} \\ \\ \frac{dM}{d\delta} \\ \\ \frac{dI}{d\delta} \end{pmatrix} = \text{sign}\begin{pmatrix} \underbrace{C_{11}C_{22} - C_{12}^2}_{>0} + \underbrace{2D_{11}}_{>0}\underbrace{\left[C_{22} - C_{12}\frac{\partial m}{\partial I}\right]}_{>0} \\ \\ -\underbrace{D_{12}}_{>0}\underbrace{\left[C_{22} - C_{12}\frac{\partial m}{\partial I}\right]}_{>0} \\ \\ \underbrace{D_{12}}_{>0}\underbrace{\left[C_{21} - C_{11}\frac{\partial m}{\partial I}\right]}_{<0} \end{pmatrix}. \tag{A.11}$$

The signs are unambiguous: $dA/d\delta > 0$, $dM/d\delta < 0$ and $dI/d\delta < 0$. This can be shown (after some tedious math) by substituting $\partial m/\partial I$ from appendix 3, inserting the definition of $\det_3$, and rearranging terms such that $\left[C_{21} - C_{11}\frac{\partial m}{\partial I}\right] < 0$ and $\left[C_{22} - C_{12}\frac{\partial m}{\partial I}\right] > 0$. Again, continuity implies that the results hold true even for slightly asymmetric countries.

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