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Investment and adaptation as commitment devices in climate policy deteriorate mitigation

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preliminary version

Abstract

The strategy of adaptation to climate change has become a central topic within the UNFCCC negotiations in recent years. On the national level, adaptation plans are elaborated, and on the international level, the need for funding adaptation in developing countries is discussed. This tendency shows that adaptation is likely to be advanced relative to mitigation on the political agenda. Therefore, we analyze the economic consequences of the timing of mitigation and adaptation in a game-theoretic framework regarding as well the importance of technological investments for mitigation. Due to strategic behavior, the activity in mitigation deteriorates when adaptation is advanced. As a consequence, the resulting subgame-perfect equilibrium yields higher total costs. We demonstrate that this result is even reinforced when technological investments are regarded, i.e. the negative effects of advancing adaptation relative to the opposite timing are amplified.

JEL classification: Q54, H41, H87, C72

Keywords: Climate change, adaptation, mitigation

1 Motivation

Following the setback of international mitigation efforts after Copenhagen (COP15) adaptation to climate change has gained increasing attention in UNFCCC negotiations. The conference of the parties in Durban (COP17) launched the Green Climate Fund (GCF) with an explicit provision of a 'balanced allocation of resources for adaptation and mitigation activities'. Many developing countries in GCF view this provision to imply a share of funding for adaptation of at least fifty percent. At the same time many developed countries kick-started adaptation strategies at home on the national and local level (Biesbroek et al. 2010). The 'taboo on adaptation' (Pielke et al. 2007) of 1990s climate negotiations has since been lifted (The Economist 2008). 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 seen as a low-cost option compared to mitigation. And, indeed, the current German experience to cut carbon emissions with renewable energy as part of the 'Energiewende' high-lights the immense infrastructural cost of an ambitious mitigation effort (The Economist 2012), lending strong evidence to Yohe's early finding on the importance of a 'mitigative capacity' to mirror 'adaptive capacity' on the mitigation side (Yohe, 2001).

The strategic implications of these new developments in mitigation and adaptation policies for the international process to protect against climate change have been neglected in much of the literature.¹ Contrary to Zehaie (2009) who focuses on a 'semi-cooperative' approach, i.e. negotiations on mitigation while adaptation as 'self-protection' is chosen non-cooperatively, the present paper bases on the finding that international negotiations on climate change under the roof of the UNFCCC are not really cooperative. In fact, the actual situation of climate change is reflected best by a purely non-cooperative setting since actual commitments under the UNFCCC-regime do not go beyond 'business as usual' contributions (see Böhringer and Vogt 2003 and 2004). Thus, the present paper further qualifies Zehaie's 'semi-negotiations' in a purely non-cooperative setting confirming his finding that the timing of adaptation before mitigation worsens the overall outcome in terms of total cost, so that mitigation should advance adaptation despite the adverse commitment effect in international negotiations of large scale investments in mitigative capacity.

Going beyond the model of Zehaie, we investigate the consequences of the strategic choice of technological investments as a further decision variable which directly affects mitigation costs. The strategic relationship of private investment in the con-

¹A paper Zehaie (2009) is one of the rare exceptions. He demonstrated that the sequencing of adaptation before mitigation could have a detrimental effect on the outcome of international negotiations, since countries could use domestic adaptation strategically to channel mitigation efforts to foreign countries, resulting in an overall lower global mitigation level.

text of international and global externalities has been analyzed from different perspectives (i.e. Buchholz and Konrad 1994, Stranlund 1996, Aggarwal and Narayan 2004). The general finding of this literature is that countries strategically underachieve their level of investments in order to shift the environmental burden to other countries. With regard to the sequencing of adaptation and mitigation, we demonstrate that the negative effect of timing adaptation before mitigation even increases relative to the reverse timing when the choice of technological investments is taken in consideration. Our overall finding is that a more cautious approach on adaptation in climate politics could be superior to the current 'rush to adaptation'.

The paper is organized as follows. In section 2 we describe the economic framework presenting the basic model and defining the efficiency benchmark. Moreover, the sequential timing of adaptation and mitigation 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. Finally, section 4 focuses on the decision on private technological investments and investigates its impact on the overall outcome comparing the cases of sequencing adaptation before and after mitigation. A short conclusion follows.

2 Economic Framework

We regard a static model of climate change in a two-country setting following the existing literature (e.g. Zehaie 2009, 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 and decreases global damage costs while adaptation is (typically) modelled as a private good and thus yields national benefits only (see e.g. Buob and Stephan 2011, Ebert and Welsch 2012, Zehaie 2009). Unlike the preceding literature, in our model the countries dispose of a third strategy: By expenditures for investment I a country enhances its mitigative capacity; i.e. the cost of mitigation decreases. Total costs accruing from climate change for the home and the foreign country are given by

$$T(M, m, A, I) = D(M + m, A) + A + C(M, I) + I \tag{1}$$

$$t(M, m, a, i) = d(M + m, a) + a + c(m, i) + i.$$

Capital (lowercase) letters denote functions and variables of the home (foreign) country. Home country's damage costs originated by climate change are expressed

by $D(M + m, A)$ which is twice continuously differentiable and strictly convex². Thus, damage cost of home is decreasing in (domestic and foreign) mitigation as well as in domestic adaptation with diminishing marginal returns. Moreover, increasing mitigation entails a decrease of the marginal effectivity of adaptation and vice versa. The costs of mitigation $C(M, I)$ are assumed to be strictly convex, $C_1 > 0$, $C_{11} > 0$, and they crucially depend on technological investment I in the following way: $C_2 \leq 0$, $C_{22} > 0$ as well as $C_{12} < 0$ ³.

In contrast, costs of adaptation are assumed to be linear. We take up the reasoning of Ebert and Welsch (2011:51ff), who model the expenditures of adaptation instead of adaptation in physical units due to the heterogeneity of measures that adaptation comprises⁴. Based on the same rationale, the costs of investment are assumed to be linear as well. Foreign country's total costs have analogous properties.

In the following, we evaluate how the sequence of the decisions on adaptation, mitigation and investment affects the non-cooperative equilibrium while the cooperative allocation serves as an efficiency benchmark.

2.1 Efficiency Benchmark

In case of full cooperation, countries minimize aggregate costs $T(M, m, A, I) + t(M, m, a, i)$. As efficiency requires full control of all variables, the timing of the decisions on investment, mitigation, and adaptation does not matter (Zehaie 2009). 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 the private strategies investment and adaptation, an efficient allocation is characterized by marginal costs which are equal to the corresponding marginal 'benefits' which, in each case, occur on a national level only. As investment lowers the costs of mitigation, marginal costs of mitigation with respect to investment can be inter-

²The 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 $D_2 = \frac{\partial D}{\partial A}$, and accordingly $C_1 = \frac{\partial C}{\partial M}$ and $C_2 = \frac{\partial C}{\partial I}$. Furthermore, damage has the following properties: $(D_1, D_2) < 0$; $(D_{11}, D_{22}, D_{12}) > 0$ and $D_{11}D_{11} - D_{12}^2 > 0$.

³Moreover, Inada conditions are assumed to hold: $\lim_{I \rightarrow 0} C_2 = -\infty$, $\lim_{I \rightarrow \infty} C_2 = 0$.

⁴Adaptation costs can also depend on technological innovation but the link between adaptation costs and technology is considerably weaker than between mitigation costs and technology. This is because adaptation measures mainly consist of the prevention or removal of subsequent 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).

preted as marginal benefits. In case of adaptation, marginal benefits are expressed by marginal damage costs. In contrast to these private strategies, the public good mitigation 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 Timing

In contrast to full cooperation, timing affects the decisions on mitigation, adaptation and investment substantively in the non-cooperative case. In order to analyze the strategic effect of timing on the non-cooperative equilibrium, we set up a sequential game with three stages. Investment is necessarily made in the first stage as it can only influence the costs of climate change if it is taken in advance. However, depending on the type of adaptation, mitigation can be fixed before, simultaneously with, or after adaptation.

In the literature it is sometimes argued that, naturally, mitigation is fixed before adaptation because of its long term effects (see, e.g. Buob and Stephan 2011, Ebert and Welsch 2012). But adaptation also can be fixed in advance; for instance, there is facilitative adaptation which enhances the adaptability of the population (Tol 2005), and adaptation with characteristics of investment (Zehaie 2009). Auerswald et al. (2011) also take up the sequencing of adaptation being fixed before mitigation and analyze the impact of risk preferences. Therefore, we assume that both cases of sequential timing regarding adaptation and mitigation are relevant.

Since a simultaneous choice can be reproduced by the sequential game of fixing mitigation before adaptation (Zehaie 2009), we do not need to consider this case separately⁵. Instead, we concentrate on the two alternative cases of sequential decision making and contrast the results with the efficiency benchmark.

3 Adaptation and Mitigation

In this section, we analyze the subgame-perfect equilibria for either case of timing by applying backward induction. We first solve the last two stages separately disregarding the choice of investment and, moreover, we 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 subsequently in section 4.

⁵However, the equivalence of the sequential timing with mitigation being fixed before adaptation and the simultaneous choice may not hold if climate funding is regarded (see Heuson et al. 2012).

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 first-order conditions

$$1 + D_2 = 0 = 1 + d_2, \quad (3)$$

which are similar to the cooperative case, i.e. marginal costs of adaptation are equal to marginal benefits. 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 in the third stage, i.e. in equilibrium we have $A(M + m)$ 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 respect to M yields the following first-order condition

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

for the home country. An 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 even in the sequential game where adaptation is anticipated.⁶

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

$$C_1 + D_1 = 0 = c_1 + d_1. \quad (5)$$

⁶By the implicit function theorem it can be shown that $-1 < \frac{dM}{dm} = -\frac{D_{11}D_{22} - D_{12}^2}{D_{22}C_{11} + D_{11}D_{22} - D_{12}^2} < 0$. These relations hold due to convexity of the damage function D .

These conditions can be explained analogously to (4). Again, mitigation of home and foreign are strategic substitutes.⁷ 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

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

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

In sum, domestic 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: $\frac{\partial[M+m]}{\partial A} < 0$.⁸ The analogous first-order condition and reasoning hold for the foreign country.

3.3 Consequences of Timing

Disregarding the choice of investment, we compare the non-cooperative mitigation and adaptation 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. There are no strategic effects and the equilibrium is identical to the one for simultaneous moves (cf. Zehaie 2009). For the reverse timing, the system of (5) and (6) yields subgame-perfect levels of mitigation and adaptation $(A^\Delta, a^\Delta, M^\Delta, m^\Delta)$, where adaptation increases due to a strategic effect as described in the previous section. Comparing these two subgame-perfect equilibria gives rise

⁷However, strategic substitutability changes with timing 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 that elastic as for the opposite timing.

⁸See Appendix 1 and cf. Zehaie (2009) for a similar result.

to

Proposition 1 *Consequences of a strategic commitment in adaptation.*

i) *If adaptation is chosen before mitigation, both countries raise their levels of adaptation due to strategic reasons compared to the reverse sequence: $(A^\Delta, a^\Delta) > (A^\circ, a^\circ)$.*

ii) *Due to this strategic increase in adaptation, the global contribution to mitigation in the subgame-perfect equilibrium of the sequence when adaptation is chosen before mitigation is lower than in the opposite case: $(M^\Delta, m^\Delta) < (M^\circ, m^\circ)$.*

Proof. i) We compare the first-order conditions regarding adaptation in the non-cooperative cases, (3) and (6). Due to the strategic effect in (6), there arise additional benefits from adaptation when it is chosen before mitigation. As marginal costs of adaptation remain unchanged, both countries choose a higher level of adaptation compared to the opposite sequence, i.e. $(A^\Delta, a^\Delta) > (A^\circ, a^\circ)$.

ii) Moreover, the first-order conditions regarding mitigation, (4) and (5), are identical. A higher level of adaptation induces a lower national marginal benefit of mitigation. Thus, the contribution to mitigation of each country decreases. Since mitigation in home and foreign are strategic substitutes, the declines are partially compensated. Nevertheless, the negative effect on mitigation outweighs the positive one in the subgame-perfect equilibrium. Consequently, the global level of mitigation is lower when adaptation is fixed before mitigation. ■

Next, let us consider the consequences of the different sequences of mitigation and adaptation 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 non-cooperative equilibrium, the subgame-perfect level of mitigation is inefficiently low: $(M^\circ, m^\circ) < (M^, m^*)$.*

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

Proposition 3 *Adaptation as a substitute to mitigation.*

In the subgame-perfect equilibrium, the level of adaptation exceeds that of the efficient allocation: $(A^\circ, a^\circ) > (A^, a^*)$.*

Proof. For both, the efficient solution and the non-cooperative equilibrium, the best choice of adaptation is characterized by identical first-order conditions (2) and (3). As mitigation in the non-cooperative 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 non-cooperative level of adaptation must exceed the efficient level. ■

Corollary 4 *Pareto ranking of the equilibria when timing matters.*

The subgame-perfect equilibrium of the sequential decision with mitigation before adaptation yields a globally superior result relative to the subgame-perfect equilibrium which results when adaptation is chosen before mitigation: $(M^ + m^*) > (M^\circ + m^\circ) > (M^\Delta + m^\Delta)$; $(A^\Delta, a^\Delta) > (A^\circ, a^\circ) > (A^*, a^*)$.*

Proof. Follows directly from Propositions 1-3. ■

When adaptation is fixed before mitigation, each country minimizes its national costs by using adaptation as a commitment in order to incentivize the neighboring country to increase its contribution to the public good mitigation. In other words, every 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 mitigation is greater than the indirect effect on the neighbor country's mitigation. Consequently, the subgame-perfect equilibrium when adaptation is fixed before mitigation is Pareto-inferior to the opposite sequence of decisions.

On the policy level, thus, it is counterproductive to advance the decision on adaptation. Due to a strategic increase in adaptation, the global level of mitigation, which is already inefficiently low, suffers from an additional downgrade. Moreover, the strategic aim of improving the own situation unilaterally cannot be achieved as other countries apply the same strategy. Therefore, the current political focus on adaptation might worsen the problem of the underprovision of the global public good mitigation. Policies should rather focus on mitigation and take adaptation as an additional emergency strategy.

4 Investment

In this section, we focus on the decision on investment in the first stage and its consequences on the subgame-perfect equilibria.

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

$$C_2 + 1 + \underbrace{[1 + D_2]}_{=0 \text{ eq. (5)}} \cdot \frac{\partial A}{\partial I} + \underbrace{[C_1 + D_1]}_{=0 \text{ eq. (6)}} \cdot \frac{\partial M}{\partial I} + D_1 \cdot \frac{\partial m}{\partial I} = 0. \quad (7)$$

For the foreign country, the first-order condition is analogous. In comparison to the efficiency benchmark (3), there arises a strategic effect which is represented by the third term in (7). With domestic and foreign mitigation as strategic substitutes, the strategic effect in (7) is positive as $\frac{\partial m}{\partial I} < 0$ (see Appendix 2). Thus, additional marginal costs of investment arise while marginal costs of investment 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 $\frac{dM}{dI} > 0$, lower investment serves as a commitment device for a low level of domestic mitigation. As domestic and foreign mitigation are 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 $\frac{d[M+m]}{dI} = \frac{-C_{12}}{\det} c_{11} > 0$ (see Appendix 2).

4.2 Adaptation before mitigation

We analyze the decision on investment when adaptation is fixed before mitigation. Minimizing total costs with respect to investment yields the following first-order condition:

$$C_2 + 1 + \underbrace{\left[1 + D_2 + D_1 \frac{\partial m}{\partial A}\right]}_{=0 \text{ eq. (5)}} \cdot \frac{\partial A}{\partial I} + \underbrace{[C_1 + D_1]}_{=0 \text{ eq. (7)}} \cdot \frac{\partial M}{\partial I} + D_1 \cdot \frac{\partial m}{\partial I} = 0. \quad (8)$$

This condition is similar to (7), and therefore, the reasoning is analog: Investment serves as a commitment device to a lower level of mitigation which in turn raises the foreign mitigation effort. Although mitigation in the home and the foreign country are strategic substitutes, the overall effect of a decline in investment on the global level of mitigation is negative as $\frac{dM+m}{dI} > 0$ (see Appendix 2). The first-order condition (and the reasoning as well) are similar 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, and the equilibrium $(M^\Delta, m^\Delta, A^\Delta, a^\Delta, I^\Delta, i^\Delta)$ with adaptation before mitigation is defined by (5), (6) and (8). Now we compare the subgame-perfect equilibria to the efficient allocation $(M^*, m^*, A^*, a^*, I^*, i^*)$. This gives rise to

Proposition 5 *Reduced mitigation effort due to underinvestment in technology. Independent of the sequence of mitigation and adaptation, countries underinvest in technology in the first stage relative to the efficient solution. This strategic behavior arises in order to commit to a lower level of mitigation in the subsequent stages.*

Proof. We compare the first-order conditions with regard to investment, (7) and (8), to the efficient solution (2). Due to the strategic effect on investment in (7) and (8), marginal benefits of investment decrease and thus, the countries choose a lower level of investments compared to the efficiency benchmark, i.e. $(I^\circ, i^\circ), (I^\Delta, i^\Delta) < (I^*, i^*)$. In the subsequent stages, a lower level of investment induce higher marginal costs of mitigation. Thus, for the identical first-order conditions with regard to mitigation, (4) and (5), to hold, domestic mitigation must be lower compared to the case without investment. Although the neighbor country compensates the decrease in mitigation partially, the net effect is negative. In sum the level of mitigation is globally lower than in the efficient allocation: $(M^\circ + m^\circ), (M^\Delta + m^\Delta) < (M^* + m^*)$. ■

Proposition 6 *Adaptation being fixed before mitigation remains Pareto-inferior. In the subgame-perfect equilibrium when adaptation is fixed before mitigation, the level of investments is smaller than in the opposite sequential decision. Moreover, the level of adaptation is higher in this sequence. Therefore, the global level of mitigation in equilibrium is lower, and, consequently, the subgame-perfect equilibrium remains Pareto-superior compared to the subgame-perfect equilibrium with adaptation being fixed before mitigation.*

Proof. With adaptation being fixed before mitigation, the level of investment of the subgame-perfect equilibrium is lower than in the reverse sequence (see Appendix 3). Due to this strategic underinvestment, marginal costs of mitigation increase. Moreover, if adaptation is chosen before mitigation, a strategic increase in adaptation induces lower benefits of mitigation (see Prop. 1). Thus, both strategic effects induce incentives to decrease the level of mitigation. This decrease is just partially compensated by mitigation in the neighbor country. Since the first-order conditions with respect to mitigation, (4) and (5), are identical, the global level of mitigation in equilibrium is lower if adaptation is fixed before mitigation. In accordance with Corollary

4, the resulting subgame-perfect equilibrium with adaptation being fixed before mitigation remains Pareto-inferior to the sequence of mitigation before adaptation also if investment is regarded in the first stage as $(M^\Delta + m^\Delta) < (M^\circ + m^\circ) < (M^* + m^*)$.

■

Independently 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. As the respective neighbor country just partially compensates the decline in mitigation, the global level of mitigation in the subgame-perfect equilibrium is lower due to the strategic behavior.

However, in the sequential case of adaptation being fixed before mitigation, the level of investment in equilibrium is even lower. Moreover, in this sequence, an additional incentive to choose a lower level of mitigation arises due to strategic adaptation. Therefore, the global level of mitigation in the subgame-perfect equilibrium is smaller and the result of section 3.3 remains qualitatively unchanged: As the global level of mitigation is suboptimally low in the non-cooperative equilibrium in general (see Prop. 2), the sequence of adaptation before mitigation yields a Pareto-inferior subgame-perfect equilibrium to the one which results if mitigation is chosen before adaptation.

Therefore, up-front investment decisions reinforce the policy proposal: Promoting early action in adaptation increases the global costs stemming from climate change. Thus, efficiency suffers from adaptive measures in advance. Therefore, the political focus should rather be put on adaptation which serve as emergency reliefs.

5 Conclusion

In recent years, the strategy of adaptation to climate change has gained increasing attention on the national and international level as national adaptation strategies are elaborated and diverse adaptation funds were launched. Therefore, decision of adaptation is likely to be advanced in the political discourse. In the present paper we investigate the economic consequences of this current shift of focus from mitigation to adaptation.

We base our analysis on the results of Zehaie (2009). If 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 situation of a country (see Zehaie 2009, BMF 2010 and Auerswald et al. 2011). However, the global level of mitigation declines.

This paper further analyzes the subgame-perfect equilibria of sequential timing

in comparison to the efficiency benchmark. Advancing the decision on adaptation in both countries yields a Pareto-inferior subgame-perfect allocation relative to the case when mitigation is fixed before adaptation. In other words, total costs of climate change rise in each country if the decision on adaptation is globally advanced.

In a second step, we investigate the role of investments in technology which are essential for a country's mitigative capacity. As the German 'Energiewende' illustrates, immense investments are necessary for the transmission to a low-carbon energy supply. The nature of investments requires that this decision is taken in advance, and, therefore, investments serve as (an additional) 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 underinvestments, the global level of mitigation decreases in either case of timing. Consequently, the problem of underprovision of mitigation is even more serious if investments are taken into account. Second, if adaptation is taken in advance, the level of investment in the subgame-perfect equilibrium is even lower than in the opposite sequencing with mitigation before adaptation. Thus, regarding investments the negative effect of advancing adaptation on the global level of mitigation is even intensified - and global costs of climate change increase.

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. As investments naturally must be taken in advance, this sequence cannot be influenced politically. Nevertheless, it might be useful to search for and apply those instruments which enhance the activities in technological investments in all countries.

Appendix 1: Comparative Statics Adaptation and Mitigation

In case adaptation is chosen before mitigation, it is necessary to evaluate the impact adaptation has on foreign and domestic mitigation (see section 3.2). We can determine the effect adaptation has in the second stage on mitigation in the third stage irrespective of the level of investment. Differentiating the first-order conditions of mitigation in home and foreign with respect to adaptation yields⁹

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

such that increasing domestic adaptation has a negative (positive) impact on domestic (foreign) mitigation, $\frac{\partial M}{\partial A} = -\frac{[c_{11} + d_{11}] D_{12}}{\det_1} < 0$ and $\frac{\partial m}{\partial A} = \frac{d_{11} D_{12}}{\det_1} > 0$. Adaptation is a substitute to own and a complement to foreign mitigation. However, the overall effect of adaptation on mitigation at the global level is negative $\frac{\partial [M+m]}{\partial A} = -\frac{c_{11} D_{12}}{\det_1} < 0$. The effects are analogous for foreign adaptation.

Appendix 2: Comparative Statics with regard to investment

To determine the impact investment has on the subgame-perfect equilibrium of mitigation and adaptation in stage 2 (including stage 3), we have to analyze the comparative statics of the choices on (M, m, A, a) , i.e. eqs. (3+4) or (5+6). As the optimal choices on adaptation are rather similar in either case of timing, we integrate both in a single approach such that the first-order conditions for home and foreign, respectively, are given by

$$\begin{aligned} 1 + D_2 + \delta D_1 \frac{\partial m}{\partial A} &= 0 \\ 1 + d_2 + \delta d_1 \frac{\partial M}{\partial a} &= 0. \end{aligned}$$

Here the parameter δ serves to distinguish the different cases of timing on adaptation and mitigation. If mitigation is chosen before adaptation, we have $\delta = 0$, and in the opposite case for adaptation being fixed before mitigation $\delta = 1$ (see sections 3.1 and 3.2). To simplify the analysis, we assume in what follows that $\frac{dm}{dA}$ and $\frac{dM}{da}$ are approximately constant and thus independent of mitigation and adaptation itself. To be precise, this requires third-order derivatives of $C(\cdot)$ and $D(\cdot)$ to be sufficiently small or ideally zero which will be true for quadratic cost functions.

⁹The 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).

Totally differentiating the first-order conditions of the decisions on adaptation yields

$$\begin{pmatrix} dA \\ da \end{pmatrix} = - \begin{pmatrix} \frac{[D_{21} + \delta D_{11} \frac{\partial m}{\partial A}]}{[D_{22} + \delta D_{12} \frac{\partial m}{\partial A}]} & \frac{[D_{21} + \delta D_{11} \frac{\partial m}{\partial A}]}{[D_{22} + \delta D_{12} \frac{\partial m}{\partial A}]} \\ \frac{[d_{21} + \delta d_{11} \frac{\partial M}{\partial a}]}{[d_{22} + \delta d_{12} \frac{\partial M}{\partial a}]} & \frac{[d_{21} + \delta d_{11} \frac{\partial M}{\partial a}]}{[d_{22} + \delta d_{12} \frac{\partial M}{\partial a}]} \end{pmatrix} \begin{pmatrix} dM \\ dm \end{pmatrix}, \quad (\text{A.2})$$

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

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

$$\begin{aligned} & \begin{pmatrix} C_{11} + D_{11} & ; & D_{11} \\ d_{11} & ; & c_{11} + d_{11} \end{pmatrix} \begin{pmatrix} dM \\ dm \end{pmatrix} + \begin{pmatrix} D_{12} & 0 \\ 0 & d_{12} \end{pmatrix} \begin{pmatrix} dA \\ da \end{pmatrix} \\ & = - \begin{pmatrix} C_{12} & 0 \\ 0 & c_{12} \end{pmatrix} \begin{pmatrix} dI \\ di \end{pmatrix}. \end{aligned} \quad (\text{A.3})$$

Substituting $(dA; da)$ from A.2 in A.3, rearranging terms and solving the equation system for the change in mitigation, yields

$$\begin{pmatrix} dM \\ dm \end{pmatrix} = \frac{- \begin{pmatrix} C_{12} \left\{ c_{11} + \frac{d_{11}d_{22} - [d_{12}]^2}{d_{22} + \delta d_{12} \frac{\partial M}{\partial a}} \right\} - \frac{c_{12} [D_{11}D_{22} - [D_{12}]^2]}{D_{22} + \delta D_{12} \frac{\partial m}{\partial A}} \\ - \frac{C_{12} [d_{11}d_{22} - [d_{12}]^2]}{d_{22} + \delta d_{12} \frac{\partial M}{\partial a}} & c_{12} \left\{ C_{11} + \frac{D_{11}D_{22} - [D_{12}]^2}{D_{22} + \delta D_{12} \frac{\partial m}{\partial A}} \right\} \end{pmatrix} \begin{pmatrix} dI \\ di \end{pmatrix}}{\det_2},$$

where determinant $\det_2 = \left\{ \frac{C_{11} [D_{22} + \delta D_{12} \frac{\partial m}{\partial A}] + D_{11} D_{22} - D_{12}^2}{D_{22} + \delta D_{12} \frac{\partial m}{\partial A}} \right\} \left\{ \frac{c_{11} [d_{22} + \delta d_{12} \frac{\partial M}{\partial a}] + d_{11} d_{22} - d_{12}^2}{d_{22} + \delta d_{12} \frac{\partial M}{\partial a}} \right\} - \left\{ \frac{D_{11} D_{22} - D_{12}^2}{D_{22} + \delta D_{12} \frac{\partial m}{\partial A}} \right\} \left\{ \frac{d_{11} d_{22} - d_{12}^2}{d_{22} + \delta d_{12} \frac{\partial M}{\partial a}} \right\} > 0$ is always positive such that the Nash equilibrium is again stable and unique (Tirole 1988).

Comparative statics show that domestic investments are a substitute (complement) to foreign (domestic) mitigation, $\frac{\partial m}{\partial I} = \frac{C_{12}}{\det_2} \left[\frac{d_{11}d_{22} - [d_{12}]^2}{d_{22} + \delta d_{12} \frac{\partial M}{\partial a}} \right] < 0$ and $\frac{\partial M}{\partial I} = -\frac{C_{12}}{\det_2} \left[c_{11} + \frac{d_{11}d_{22} - [d_{12}]^2}{d_{22} + \delta d_{12} \frac{\partial M}{\partial a}} \right] > 0$. Moreover, investments encourage mitigation efforts globally $\frac{\partial(M+m)}{\partial I} = -\frac{C_{12}c_{11}}{\det_2} > 0$. 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 sequence of adaptation and mitigation since $\frac{\partial M}{\partial a}, \frac{\partial m}{\partial A} > 0$ (see Appendix 1).

Appendix 3

To compare the effects of investment in the two different sequential games, we evaluate the levels of investment chosen in the subgame-perfect equilibria. The first-order conditions with respect to investment, 7 and 8, are identical. However, the equilibrium level of investment depends on adaptation and mitigation which differ according to timing. As shown in Appendix 2, the difference between both cases can be indicated by the parameter δ^{10} . Therefore, the first-order conditions (7) and (8) can be represented as a function of δ and I , i.e. $F(\delta, I) \equiv 1 + C_2 + D_1 \frac{\partial m}{\partial I} = 0$. By the implicit function theorem, it can be shown that

$$\frac{\partial I}{\partial \delta} = -\frac{F_\delta}{F_I}.$$

In order to determine the sign of this equation, we need to analyze F_δ and F_I . First, we take the derivative of F with respect to δ which yields

$$F_\delta = C_{12}M_\delta + \{D_{11}[M_\delta + m_\delta] + D_{12}A_\delta\} \frac{\partial m}{\partial I}. \quad (\text{A.4})$$

Taking the derivative of the first-order condition of mitigation, i.e. $C_1 + D_1 = 0$, with respect to δ yields

$$-C_{11}M_\delta = D_{11}[M_\delta + m_\delta] + D_{12}A_\delta.$$

Inserting this and $\frac{dm}{dI} = \frac{C_{12}}{\det} \left[\frac{d_{11}d_{22} - [d_{12}]^2}{d_{22} + \delta d_{12} \frac{\partial M}{\partial a}} \right]$ into A.4 and rearranging terms yields

$$F_\delta = C_{12} \left[1 - C_{11} \frac{d_{11}d_{22} - [d_{12}]^2}{\det_2 \left[d_{22} + \delta d_{12} \frac{\partial M}{\partial a} \right]} \right] M_\delta.$$

The sign of F_δ mainly depends on the term in square brackets. By inserting the definition of \det_2 and rearranging terms, it can be shown (after some tedious math) that $[\cdot]$ is always positive.

F_δ is positive due to $M_\delta < 0$, which was shown in section 3.3. With $F_I = C_{22} > 0$, we can determine the impact δ has on I

$$\frac{\partial I}{\partial \delta} = -\frac{F_\delta}{F_I} < 0.$$

As investment increases with $\delta \in [0; 1]$, we know that $I(0) = I^\Delta < I(1) = I^\circ$. Thus, we conclude that the level of investments is higher when mitigation is fixed before adaptation.

¹⁰For mitigation being fixed before adaptation, $\delta = 0$, and in the reverted case, $\delta = 1$.

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