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On the Relationship between Adaptation and Mitigation

Abstract

Many poor countries are ill-adapted to the current leave alone a changing future climate, because they lack the necessary financial means to invest in efficient and cost-effective safeguarding measures. International endeavours to fund institutions, such as the Green Climate Fund, to provide financial assistance in this respect have not been as successful has hoped for. In this paper, I set up a simple two-player two-stage model, in which a rich country (North) can invest into adaptation measures in a poor country (South). I show that a necessary condition for North to invest into adaptation investments in South is that this results in decreasing equilibrium emissions of South. I find that this can only happen if the funded adaptation measures also have a flavor of mitigation, i.e., apart from safeguarding South from climate damages they have to reduce South's marginal abatement costs. My results have important policy implications for the selection of adaptation and mitigation projects by international adaptation funding organizations, such as the Green Climate Fund.

JEL-Codes: C720, D620, H410, Q540, Q580.

Keywords: climate change, adaptation versus mitigation, cross-country adaptation investments, non-cooperative climate policy, strategic complementarity.

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1 Introduction

While mitigation (i.e., the abatement of greenhouse gas emissions) remains the prime strategy to combat anthropogenic climate change, the already realized and also future increase in global average surface temperature and the accompanied changes in climatic parameters render adaptation strategies to safeguard human health and economic interests inevitable. Yet, many of the poorer countries around the globe are maladapted (i.e., “under”-adapted) to the current leave alone a potential future climate. This is apparent from recurring mass destructions caused by extreme weather events, such as the recent floods in summer and autumn 2022 in Pakistan, which affected 33 million people of which more than 1730 were killed and flood damages and economic losses amounted to more than USD 30 billion (The World Bank 2022).

Not only do poor countries suffer from the effects of anthropogenic climate change caused by the past greenhouse gas (GHG) emissions of the developed world, they often also lack the necessary funds to sufficiently invest into their own protection. This dilemma has been acknowledged by the world community and negotiations about transfers from rich to poor countries take place under the “loss and damage” chapter of the UNFCCC negotiations. An offspring of this strand is the Green Climate Fund founded in 2010 at COP16 in Cancún, the goal of which was to provide USD 100 billion per year from 2020 onward to fund adaptation and mitigation projects in developing countries. According to the Green Climate Fund’s own website, committed contributions currently sum up to USD 11.4 billion. Also the latest “loss and damage” negotiations at the COP27 in Sharm El-Sheikh were only deemed as partly successful (The New York Times 2022).

In this paper, I investigate if and under what conditions a rich country (i.e., a country that is not credit constrained), called North, has an incentive to fund adaptation measures in a poor country (i.e., a country that is – for whatever reasons – credit constrained and, thus, cannot afford efficient protection measures), called South. To this end, I introduce a simple two stage game, in which North decides whether to fund adaptation measures in South in the first stage. In the second stage, both countries simultaneously and non-cooperatively chose domestic emission levels. Countries’ welfare functions are composed of benefits accruing from domestic emissions and climate damages depending on the level of global emissions.

I find that a necessary condition for North to have an incentive to fund adaptation measures in South is that South’s equilibrium emissions decrease, as decreasing emissions is the only “currency” by which South can remunerate North for the costs of adaptation investments. I further show that for South’s equilibrium emissions to decrease, adaptation investments must also have a flavor of mitigation: In general, adaptation measures decrease absolute and marginal damages suffered from any given level of global emissions. This leads to an incentive for South to increase its equilibrium emissions, as the costs of emissions (in terms of climate damages) are now smaller. For South's emissions to decrease in equilibrium, this incentive to increase emissions has to be outweighed by a countervailing incentive to decrease emissions in equilibrium. Such an incentive is provided if adaptation investments also decrease the marginal abatement costs sufficiently.

Employing a quadratic benefit function specification, I illustrate how adaptation measures have to impact mitigation by affecting not only the damages from global emissions but also the benefits from domestic emissions for positive adaptation investments to be in North's best interest. Projects that apart from safeguarding against climate damages reduce marginal benefits, respectively abatement costs, without reducing absolute benefits are likely candidates for funding. While projects exhibiting the necessary conditions North would be happy to fund may well and truly exist, they are probably rather the exception than the rule. I also show that these insights are qualitatively robust to a variety of model extension.

My results have important policy implications. First, they may explain why international funding agencies like the Green Climate Fund have a hard time to secure sufficient funding from rich countries to invest in adaptation measures in poor countries, as this may not be in the best interest of the former. Second, my results also show what kind of adaptation measures are likely to be in the best interest of the funding countries and, thus, provide a basis for project selection. Finally, the problem of adaptation funding being not in the best interst of donor countries might be circumvented by appropriate bundling of adaptation and mitigation projects.

The remainder of the paper is structured as follows. Section 2 briefly reviews the relevant literature. The baseline model is introduced in Section 3 and analyzed in Section 4. Section 5 illustrates the results by employing a quadratic benefit function. In Section 6, I show that the insights of the baseline model carry over to various model extensions. Finally, Section 7 discusses the results with respect to real world climate policies and concludes.

2 Literature

My paper relates to the literature analyzing the relationship between mitigation adaptation in the context of transboundary pollutants such as GHG emissions. Most of these papers analyze situations in which countries optimally choose their own adaptation and mitigation levels, i.e., adaptation becomes an additional choice variable of countries on top of mitigation (e.g, Zehaie 2009, Buob and Stephan 2011, Onuma and Arino 2011, Ebert and Welsch

2012, Ingham et al. 2013). In most of these models, adaptation and mitigation are strategic substitutes, i.e., increases in own adaptation are accompanied with reductions in own mitigation. The reason is straight forward: lower damages from global emissions increase ceteris paribus the amount of domestic emissions for which marginal damages from global emissions and marginal benefits from domestic emissions coincide. In addition, if emission choices across countries are strategic substitutes, higher own emissions are accompanied by emissions reductions in other countries, i.e., part of the abatement burden can be rolled over to other countries. Buob and Stephan (2011) and Ingham et al. (2013) find that adaptation and mitigation choices within a country may become strategic complements if adaptation decreases mitigation costs. The strategic substitutability between mitigation and adaptation leads to over-investment into adaptation and under-investment into mitigation compared to the efficient allocation (e.g., Ebert and Welsch 2012 and Schumacher 2019).

Another strand of the literature investigates the relationship between mitigation and adaptation in the formation of international environmental agreements. Benchekroun et al. (2017), Li and Rus (2019) and Barrett (2020) consider model frameworks in which one countries adaptation and mitigation choices are strategic substitutes, i.e., if protection against climate damages increases also emission choices in equilibrium rise. As such, the possibility of adaptation increases overall emissions compared to a situation of no adaptation. However, the possibility of adaptation may increase the membership size of an agreement. The reason is that adaptation improvements within the coalition increases the coalition's equilibrium emissions, which leads to decreasing equilibrium emissions by non-members of the agreement, because emission choices are strategic substitutes. This increases the welfare of the coalition and may render larger coalition sizes stable. Breton and Sbragia (2019) analyze international agreements in which the coalition in addition to mitigation also coordinates on adaptation. They find that these agreements allow for larger stable coalition sizes up to the grand coalition. Bayramoglu et al. (2018) analyze a model set-up in which mitigation choices of countries can turn in strategic complements. This can happen when the absolute value of the cross derivative of benefits with respect to mitigation and adaptation is sufficiently large. Also in this case, larger coalition sizes up to the grand coalition can be stable. Finus et al. (2021) extends this analysis to a Stackelberg game, in which the coalition moves first.[1]

The papers most closely related to this work are Buob and Stephan (2013) and Sakamoto et al. (2020), which are – to the best of my knowledge – the only papers that investigate adaptation funding from rich (North) to poor (South) countries in a non-cooperative game

[1] Eisenack and Kähler (2016) analyze a similar setting with respect to timing, but investigate only strategic interactions across two countries.

setting.[2] While Buob and Stephan (2013) analyze a Stackelberg setting, where North moves first with respect to both emissions (respectively mitigation) and adaptation investments in South, Sakamoto et al. (2020) employ a similar timing as this paper: North first decides on adaptation investments in South in the first stage and both countries simultaneously chose emissions in the second stage. Both also find that South's mitigation choice and North's adaptation investments have to be strategic complements, i.e., South's emissions in equilibrium decrease in North's adaptation investments. While Buob and Stephan (2013) are rather pessimistic that this is the case, Sakamoto et al. (2020) analyze a very specific model set-up, in which this complementarity is easier to achieve. My conclusions are somewhere in between: While I do not confine the analysis to a particular channel and specific functional forms, which are relatively likely to result in the necessary complementarity, I rather scrutinize in a general model framework what are the characteristics adaptation measures funded by North have to exhibit in order to be in its best interest.

3 The Model

Consider a world with only two countries, which I call North (N) and South (S). North denotes a developed country, while South is a developing country or country in transition. I assume that North has access to better technology leading, in general, to higher GDP per capita, higher carbon efficiency (i.e., GDP produced per unit of GHG emissions) and higher willingness-to-pay to avoid damages from anthropogenic climate change.

Domestic welfare of country $i = N, S$ is given by a country specific benefit function B_i that depends on its domestic GHG emissions $e_i \geq 0$ minus country specific damages D_i that are caused by global emissions $E = e_N + e_S$. In addition, I assume that North can finance adaptation measures in South, which South could not afford on its own, i.e., I consider South is credit constrained. The higher the adaptation investments $a \geq 0$ of North, the smaller are South's damages and marginal damages from climate change for any level of global emissions E, i.e., $\partial D_S/\partial a < 0$ and $\partial^2 D_S/(\partial e_S \partial a) < 0$. However, adaptation investments a may also influence South's benefit function B_S. Then, we can write domestic welfare of the

[2] Eyckmans et al. (2016) analyze different kinds of financial aid from richer (North) to poorer (South) countries, also including adaptation investments. Yet, they assume that North does so for ethical rather than strategic reasons (see also Section 7). They argue that there is a high risk that North's financial transfers simply crowd out South's own investments apart for very poor and credit constrained countries. In fact, I assume that without North's adaptation investment South would not be able to provide adaptation on its own.

North and South as:

$$W_N = B_N(e_N) - D_N(E) - a \ , \tag{1a}$$

$$W_S = B_S(e_S, a) - D_S(E, a) \ . \tag{1b}$$

I employ the standard assumptions that benefits B_i are increasing and strictly concave in domestic emissions e_i, while damages from climate change D_i are increasing and convex in global emissions E. A possible interpretation of the domestic welfare functions (1) is that benefits B_i denote country i's GDP as a function of domestic GHG emissions gross of environmental damages (and in case of North also gross of adaptation investments in South). Then environmental damages D_i denote the monetarized domestic damages for country i, for example, the willingness-to-pay of the respective country to avoid these damages.

I assume that the North's decision whether and, if so, to what extent to invest into adaptation in the South, and the North's and South's decisions on domestic GHG emissions can be modeled as a non-cooperative two-stage game, in which both countries seek to maximize their own domestic welfare:

1. **Adaptation Stage:** North chooses how much (if at all) to invest into climate change adaptation in South. South observes these investments.

2. **Mitigation Stage:** North and South simultaneously choose emission levels e_N and e_S.

Before proceeding to the analysis of this two-stage game, two important remarks are in order:

Remark 1: I assume that North's adaptation investments in South in the first stage are a *unilateral* decision of North. Of course, North cannot invest in the South without South's consent. In the following, I assume that North's adaptation investment is always beneficial for South and, thus, South will always consent to any adaptation investments made by North in the first stage of the game. As damages decrease in adaptation investments, this implies a lower bound for how South's benefits change with respect to adaptation investments a:

$$\frac{dW_S}{da} > 0 \qquad \Leftrightarrow \qquad \frac{\partial B_S(e_S, a)}{\partial a} \geq \frac{\partial D_S(E, a)}{\partial a} \ . \tag{2}$$

Remark 2: The sequence of the adaptation and mitigation stages is not innocuous. In fact, one might argue that the timing should rather be reversed, as the bulk of damages from today's GHG emissions is to be expected in the future. Thus, *within* one country the possibility to adapt to damages in the future might indeed crowd out the country's incentive to mitigate today (Buob and Stephan 2011; Ebert and Welsch 2012; Ingham et al. 2013; Onuma and Arino 2011; Zehaie 2009). However, I am rather interested in incentives of countries to invest into climate change adaptation *across* countries. If countries only consider their own welfare, they will only have an incentive to do so if this can influence the other country's emissions choice, as long as countries cannot credibly commit to future emission reductions contingent on today's adaptation investments.[3] Thus, the only interesting case arises when the adaptation stage is before the mitigation stage (Buob and Stephan 2013, Sakamoto et al. 2020). Moreover, in international climate policy it is indeed currently discussed to set up international funds to finance (also) adaptation measures in developing countries, for example, the UNFCCC Green Climate Fund founded in 2010 at COP16 in Canćun.

In the following, I shall characterize the subgame perfect Nash equilibrium of the above described non-cooperative two-stage game, which I derive by backward induction.

4 The Relationship between Adaptation and Mitigation

Suppose that North has chosen some adaptation investment level $a = \bar{a}$ in the first stage. Then, we can define the South's benefit and damage functions in stage two as:

$$\bar{B}_S(e_S) \equiv B_S(e_S, a)\big|_{a=\bar{a}} , \qquad \bar{D}_S(E) \equiv D_S(E, a)\big|_{a=\bar{a}} . \tag{3}$$

In the second stage, both countries decide on emission levels e_i to maximize their own domestic welfare, as given by (1), given the other country's emission choice and the sunk level of adaptation investments $\bar{a}$. Due to the assumed curvature properties of benefit functions B_i and damage functions D_i, the domestic welfare functions of both countries are strictly concave in domestic emissions choices e_i. As a consequence, country i's ($i = N, S$) best response is implicitly given by the first-order conditions:

$$B'_N(e_N) = D'_N(E) , \qquad \bar{B}'_S(e_S) = \bar{D}'_S(E) . \tag{4}$$

It is well known (and shown in Appendix A.1) that there exists a unique Nash equilibrium for the subgame starting in the second stage of the game characterized by domestic emission levels $\hat{e}_N(a)$ and $\hat{e}_S(a)$, and global emissions $\hat{E}(a) = \hat{e}_N(a) + \hat{e}_S(a)$. In addition, emissions choices of countries are strategic substitutes.

In the first stage, North decides how much to invest in adaptation a, anticipating the effect of its choice on second stage emissions levels. Thus, North chooses adaptation investments

[3] An investing country has to at least fear that a receiving country might not honor its promises with respect to future emission reductions in return for today's adaptation investments due to the lack of any international enforcement agency.

a to maximize:

$$W_N(a) = B_N(\hat{e}_N(a)) - D_N(\hat{E}(a)) - a \ . \tag{5}$$

Assuming that North's domestic welfare is strictly concave with respect to adaptation investments a,[4] North's optimal adaptation investment level is implicitly given by the following first-order condition:

$$B'_N(\hat{e}_N(a))\frac{d\hat{e}_N(a)}{da} - D'_N(\hat{E}(a))\frac{d\hat{E}(a)}{da} - 1 \leq 0 \ . \tag{6}$$

Note that the inequality sign stems from the possible corner solution $\hat{a} = 0$, i.e., it might be in North's best interest *not* to invest in adaptation in South at all. This always applies if the equality sign does not apply for any feasible value a of adaptation investments. Employing the second stage first-order condition (4), implying that $B'_N(\hat{e}_N(a)) = D'_N(\hat{E}_N(a))$, and taking into account $\hat{E} = \hat{e}_N + \hat{e}_s$, we can re-write the first stage first-order condition:

$$-D'_N(\hat{E}(a))\frac{d\hat{e}_S(a)}{da} \leq 1 \ . \tag{7}$$

The right-hand side denotes the costs of a marginal unit of adaptation investments (which is one, as we measure both domestic welfare and adaptation investments in monetary terms). The left-hand side are the benefits from a marginal unit of adaptation investments. They arise from a decrease in environmental damages due to a reduction in South's domestic emissions. If there exists a positive investment level $\hat{a}$ for which the equality sign holds then this is North's optimal choice. Otherwise, the North's optimal investment level is not to invest at all, i.e., $\hat{a} = 0$. In this case, the inequality sign holds for all feasible investment levels a. Condition (7) directly implies the following proposition (see Appendix A.3):

Proposition 1 (Necessary Condition for Positive Adaptation Investments) *A necessary condition for positive adaptation investments of North in the subgame perfect Nash equilibrium is that South's equilibrium emission decrease in North's adaptation investments.*

The important insight of condition (7) is that North only has an incentive to invest into adaptation in South if this decreases equilibrium emissions in South. The economic intuition is straight forward. The only way how South can "pay back" North for its adaptation investments is by North suffering less climate damages, which can only occur if South's emissions go down. As long as South cannot credibly commit to emissions reductions in return for adaptation investments of North, emissions reductions have to be an equilibrium

[4] A sufficient condition for strict concavity of North's domestic welfare with respect to a is that second stage equilibrium emissions of the South are concave in a, i.e., $d^2\hat{e}_s(a)/da^2 \leq 0$ (see Appendix A.2).

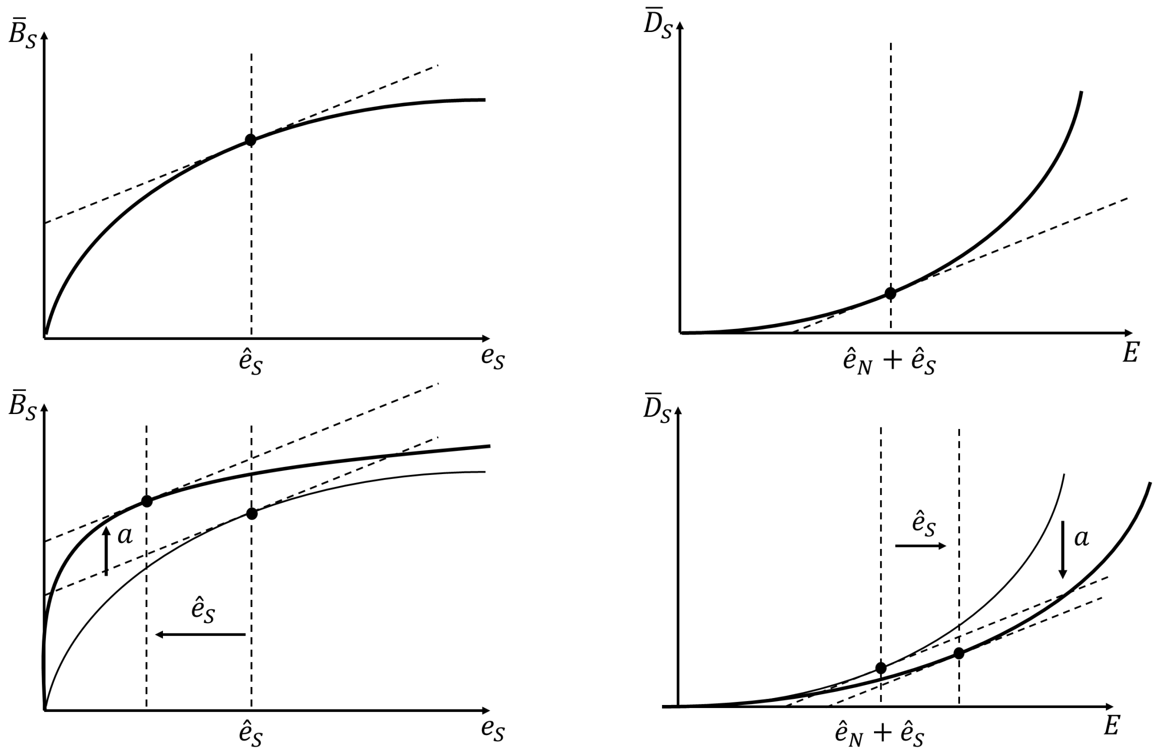

Figure 1: Illustration how equilibrium emissions of South $\hat{e}_S$ change in North adaptation investments a.

outcome, i.e., it has to be in the best interest of South to decrease its emissions in respond to adaptation investments of North. Yet, it is not sufficient for positive adaptation investments that South's emissions go down. They have to go down sufficiently strong to outweigh the costs of adaptation investments.

Having established that decreasing equilibrium emissions of South is a *necessary* condition for positive adaptation investments of North, we further explore under what circumstances this holds. We obtain the following result (see Appendix A.4):

Proposition 2 (Strategic Complementarity between Adaptation and Mitigation) *South's emissions in the Nash equilibrium of the second stage of the game are decreasing in North's choice of adaptation investments in the first stage if and only if:*

$$-\frac{\partial^2 B_S(e_S, a)}{\partial e_S \partial a} > -\frac{\partial^2 D_S(E, a)}{\partial E \partial a} \ . \tag{8}$$

Condition (8) of Proposition 2 says that equilibrium emissions of South decrease in adaptation investments of North if and only if South's marginal benefits of domestic emissions decrease stronger in adaptation investments than marginal damages from global emissions. This is illustrated in Figure 1. South's emissions choice in the Nash equilibrium of the second stage is characterized by equating South's marginal benefits and marginal climate damages (upper left and right graphs of Figure 1). North's investment in adaptation a decreases absolute and marginal damages from climate change of South. This leads ceteris paribus to an increase in South's second stage equilibrium emissions (lower right graph of Figure 1). In addition, North's adaptation investment a may also change South's benefit function. South's second stage equilibrium emissions ceteris paribus decrease if marginal benefits of South decrease in North adaptation investments (lower left graph in Figure 1). If this decrease of South's equilibrium emissions due to a change in marginal benefits outweighs the corresponding increase in emissions due to decreasing marginal damages, then South's second stage equilibrium emission decline.

Remark 3: Decreasing marginal benefits of domestic emissions are equivalent to decreasing marginal abatement costs of domestic emissions, as the flatter the benefit function is in domestic emissions, the more domestic emissions can be abated per unit of foregone GDP. Thus, another way to phrase the insight of Proposition 2 is that South's marginal abatement costs have to decline faster in North's adaptation investments than its marginal damage costs.

Remark 4: While it is straight forward that North's adaptation investments in South should influence South's damage function $D_S(E,a)$ in the way specified in Section 3, it is not necessarily straight forward that North's adaptation investments in South should have an impact on South's benefit function $B_S(e_S,a)$ at all. Note that I am not assuming or implying that North's adaptation investments have or should have an impact on South's benefit function. The point here is that in order for North to have an incentive to invest in adaptation in South in the first place, these adaptation investments must also have an impact on South's benefit function as specified by condition (8). If South's benefit function is independent of North' adaptation investments, the left-hand side of condition (8) is zero, while the right-hand side is positive and, thus, can never hold.

5 A Quadratic Benefit Function Illustration

To gain some intuition what condition (8) implies for South's benefit function, I investigate the following quadratic parametrization:

$$B_S(e_S,a) = \gamma(a) + \frac{2\alpha(a)}{\beta(a)^2} e_S \left(\beta(a) - \frac{e_S}{2}\right) , \quad \alpha(a) > 0 , \quad 0 \le e_S \le \beta(a) , \quad \gamma(a) > 0 . \quad (9)$$

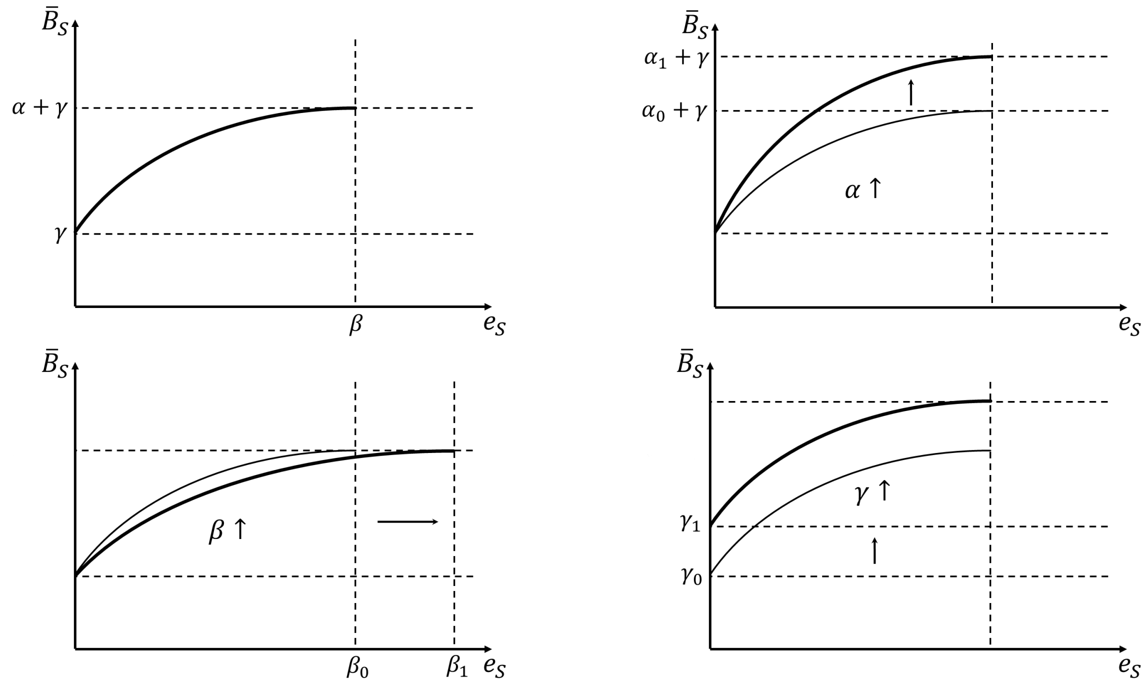

Figure 2: Illustration of the quadratic benefit function specification $\bar{B}_S$ of South and how changes in the parameters α, β and γ affect it.

As mentioned in Section 3, the benefit function B_S measures South's GDP gross of environmental damages as a function of its domestic GHG emissions e_S and North's adaptation investments a. B_S is a concave quadratic function in domestic emissions e_s, starting at γ for zero emissions and reaching the maximum level of GDP $\alpha + \gamma$ at the emission level $e_S = \beta$ (see upper left graph of Figure 2).

Thus, the parameters α, β and γ have straight forward economic interpretations. The amount of GDP produced without emitting any (net) domestic GHG emissions is given by γ. Thus, γ denotes the autonomous or GHG emission independent part of GDP. An increase in γ shifts the benefit function $\bar{B}_S$ upwards, as illustrated in the lower right graph of Figure 2. β is the amount of (net) GHG emissions that South releases into the atmosphere if it runs its economy at full capacity. An increase in β stretches South's benefit function $\bar{B}_S$ to the left, implying that the maximum emissions increase (see lower left graph of Figure 2). It also implies that for any feasible emission level $0 \leq e_S \leq \beta$ output decreases and marginal benefits decrease for all emission levels $es > \beta/2$. The parameter α denotes the amount of GDP South can produce on top of the autonomous GDP γ if it runs its economy at full capacity. An increase in α stretches South's benefit function upwards, as shown in the upper right graph of Figure 2. In addition it increases GDP and marginal GDP for any feasible emission level $0 \leq e_S \leq \beta$.

Evaluating condition (8) of Proposition 2 for South's equilibrium emissions to decrease in North's adaptation investments, we obtain (see Appendix A.5):

$$-\frac{2\alpha(a)}{\beta(a)^2}\left\{\left[2\hat{e}_S - \beta(a)\right]\frac{\beta'(a)}{\beta(a)} + \left[\beta(a) - \hat{e}_S\right]\frac{\alpha'(a)}{\alpha(a)}\right\} > -\frac{\partial^2 D_S}{\partial e_S \partial a}\ . \tag{10}$$

The right-hand side denotes the decrease in marginal damages of South due to a marginal unit of adaptation investments of North. As $\partial^2 D_S/(\partial e_S \partial a) < 0$, the right-hand side is always positive. The left-hand side is the change in South's marginal benefits due to the influence of a marginal unit of adaptation investments of North. This change can be positive or negative (a positive left-hand side implies that South's equilibrium emissions decrease because of adaptation investments impacts on South's benefit function). We observe that the left-hand side is more positive, the more negative are the changes in α and β (i.e., $\alpha' < 0$ and $\beta' < 0$).[5] The intuition is straight forward. Decreases in α and β reduce South's marginal benefits, respectively abatement costs. The lower South's abatement costs are, the stronger are its incentives to reduce emissions in equilibrium.

Remark 5: In Section 3, I have assumed that South always consents to North's adaptation investments, which is always the case if condition (2) holds. Thus, to fulfill both conditions (2) and (10) at the same time, marginal benefits have to decrease sufficiently without absolute benefits decreasing too much. Reductions in β reduce marginal benefits and increase absolute benefits for all emission levels $e_s > \beta/2$ and, thus, help to satisfy both conditions at the same time. Reductions in α, however, reduce marginal benefits but also reduce absolute benefits and, thus, relaxing condition (10) while tightening condition (2). Yet, reductions in absolute emissions could be outweighed by increases in autonomous GDP γ, which increases absolute benefits without any impact on marginal benefits.

The interesting question now is, which kind of adaptation projects satisfy condition (10)? Ideally, adaptation investments decrease β, increase γ and do neither increase nor decrease α too much in order to not reduce absolute benefits or increase marginal benefits. A possible example might be large dam projects: they provide some protection against extreme weather events (both heavy rainfall and dry spells) and, thus, clearly have positive adaptation effects. At the same time they may reduce the maximum emissions β by providing hydro power, while their effect on α and γ might be limited (i.e., $\alpha'(a) \approx 0$ and $\gamma'(a) \approx 0$). The important

[5] Note that a decrease in β renders the left-hand side of condition (10) more positive if and only if $\hat{e}_S > \beta(a)/2$, i.e., equilibrium emissions of South must not be smaller than half of the maximum emissions β. Yet, it is probably safe to assume that equilibrium emissions are not too far off the emissions at full capacity, as otherwise a lot of production capacity would lie idle. This would question the particular composition of the production technology in South in the first place.

insight is that while adaptation projects satisfying condition (10) may well and truly exist, they are far from being the general case. Most direct adaptation measures probably have either negligible effect on South's benefit function, for example, climate adapted crops, or even a detrimental effect, for example, air conditioning, which may increase the maximum emissions β due to increased energy consumption. In both cases, North has no incentive to fund such measures.

6 Model Extensions

Without doubt, the model introduced in Section 3, analyzed in Section 4 and illustrated in Section 5 is highly stylized and neglects many important issues in climate adaptation funding across countries. In the following, I shall discuss four extensions of the baseline model discussed so far, which address several of these important omissions, and investigate to what extend they change or qualify Propositions 1 and 2 of the baseline model.

6.1 Adaptation Investments also Affect North's Benefit Function

In the baseline model presented in Section 3, North's adaptation investments only affected the benefit and damage function of South. In the following, I assume that they also have an impact on North's benefit function, i.e., $B_N = B_N(e_N, a)$. I restrict attention to the case that North's benefits increase in adaptation investments, i.e., $\partial B_N(e_N, a)/\partial a > 0$. The reason is that in this case the net costs of adaptation investments decrease compared to the baseline case and, thus, it might be more likely to be in the best interest of North to fund adaptation in South in the first place. Possible channels how North's adaptation investments in South could increase North's benefits include that firms in North provide goods and services for the adaptation measures in South or – more indirectly – better climate protection in South reduces migration from South to North.

As shown in Appendix A.6, the derivation of the unique Nash equilibrium in terms of emission choices in the second stage is analogous to the baseline model discussed in Sections 3 and 4. Again, second stage emission choices of North and South are strategic substitutes. Moving to the first stage, North's necessary condition for optimal adaptation investments in South changes to:

$$-D_N'(\hat{E}(a))\frac{d\hat{e}_S(a)}{da} \leq 1 - \frac{\partial B_N(\hat{e}_N(a), a)}{\partial a} \ . \tag{11}$$

The difference to the corresponding condition (7) in the baseline model is given by the second term of the right-hand side. The economic intuition is straight forward: the net costs of a marginal unit of adaptation investments are now reduced by the positive effect of these investments on North's benefit function. However, as long as the direct costs of adaptation investments exceed the indirect benefits via an increase of North's benefit function,[6] i.e.,

$$1 - \frac{\partial B_N(\hat{e}_N(a), a)}{\partial a} > 0 \ , \tag{12}$$

Proposition 1 still holds: A necessary condition for optimal adaptation investments to be positive is that South's equilibrium emissions decline in adaptation investments.

Scrutinizing under what conditions South's equilibrium emissions decrease in adaptation investments, we find that

$$\frac{d\hat{e}_S(a)}{da} < 0 \quad \Leftrightarrow \quad -\frac{\partial^2 B_S(e_S, a)}{\partial e_S \partial a} + \frac{\bar{D}_S''(E)}{D_N''(E) - B_N''(e_N)} \frac{\partial^2 B_N}{\partial e_N \partial a} > -\frac{\partial^2 D_S(E, a)}{\partial E \partial a} \ . \tag{13}$$

The difference to the corresponding condition in Proposition 2 is the second term on the left-hand side. This term stems from the strategic substitutability of emissions choices.[7] If North increases its equilibrium emissions, South's best response is to decrease its own emissions. Consequently, this effect ceteris paribus increases South's equilibrium emissions if adaptation investments decrease North's marginal benefits of domestic emissions, respectively marginal abatement costs, as this leads to decreasing equilibrium emissions of North. Thus, whether the impact of adaptation investments on North's benefit function tightens or relaxes condition (13) depends on whether marginal benefits in North increase or decrease in adaptation investments. Yet, the spirit of Proposition 2 still holds: incentives to increase equilibrium emissions due to better protection againts climate damages have to be outweighed by other incentives to reduce equilibrium emissions.

Remark 6: I do not consider the case that adaptation investments of North in South also affect climate damages in North, i.e., $D_N = D_N(E, a)$, as this case is not interesting when considering the relationship between adaptation and mitigation across countries. If, on the one hand, adaptation investments in South also were to reduce climate damages in North than these measures were indistinguishable from mitigation efforts, which would always be beneficial for both countries. If, on the other hand, they were to increase climate damages in North this would just impose an additional cost on North rendering adaptation investments even less attractive.

[6] This assumption seems reasonable, as otherwise it would be in North' best interest anyway to fund adaptation investments in South. Obviously, such adaptation investments may exist, but they are probably not the ones which should be difficult to find funding for.

[7] Note that South's emissions choice is a dominant strategy if $\bar{D}_S'' = 0$, i.e., if South's marginal damages from global emissions are constant. In this case, the additional term vanishes and condition (13) is identical to the corresponding condition (8) in the baseline model.

6.2 Multiplicative Damages

The baseline model set-up is strongly inspired by the game theoretical literature on international climate cooperation, in which the additive separable formulation of benefits and climate damages, as in the domestic welfare functions (1), is commonplace. Yet, in models of exogenous and endogenous growth and, in particular, in integrated assessment models often a multiplicative functional form is considered (e.g., Golosov et al. 2014, Nordhaus 2018, Traeger forthcoming), in which climate damages destroy a fraction of potential production (potential meaning gross of climate damages). We now consider the following multiplicative specification of North's and South's domestic welfare functions:

$$W_N = D_N(E)B_N(e_N) - a \ , \qquad W_S = D_S(E,a)B_S(e_S,a) \ . \tag{14}$$

While the benefit function B_i are still assumed to be increasing and concave, as in the baseline model, I now assume the following properties for the damage functions:

$$D_i(0,\cdot) = 1 \ , \quad \frac{\partial D_i(E,\cdot)}{\partial E} < 0 \ , \quad \frac{\partial^2 D_i(E,\cdot)}{\partial E^2} < 0 \ , \quad \frac{\partial D_S(E,a)}{\partial a} > 0 \ , \frac{\partial^2 D_S(E,a)}{\partial E \partial a} > 0 \ . \tag{15}$$

As shown in Appendix A.7, the first-order conditions for the equilibrium choices of emissions in the second stage yield:

$$D_N(E)B'_N(e_N) = -D'_N(E)B_N(e_N) \ , \tag{16a}$$

$$\bar{D}_S(E)\bar{B}'_S(e_S) = -\bar{D}'_S(E)\bar{B}_S(e_S) \ . \tag{16b}$$

Unsurprisingly, the unique Nash equilibrium in the second stage of the game is also governed by each country equating its marginal benefits (left-hand side) to its marginal damages (right-hand side). Again, emission choices in the second stage of the game are strategic substitutes.

In the first stage, North's first-order condition for optimal adaptation investment reads:

$$D'_N(\hat{E}(a))B_N(\hat{e}_N(a))\frac{d\hat{e}_S}{da} \leq 1 \ . \tag{17}$$

As marginal damages of North are now given by $-D'_N(E)B_N(e_N)$, as can be seen from the second stage first-order conditions (16), condition (17) is perfectly analogous to the corresponding condition (7) of the baseline model. As a consequence, also Proposition 1 holds unaltered. This analogy also carries over for condition (8) of Proposition 2, which, for multiplicative damages, is given by:

$$\begin{aligned}\frac{d\hat{e}_S(a)}{da} < 0 \quad \Leftrightarrow \quad & -\left(\frac{\partial D_S(E,a)}{\partial E}\frac{\partial B_S(e_S,a)}{\partial a} + D_S(E,a)\frac{\partial^2 B_S(e_S,a)}{\partial e_S \partial a}\right) \\ & > \frac{\partial D_S(E,a)}{\partial a}\frac{\partial B_S(e_S,a)}{\partial e_S} + \frac{\partial^2 D_S(E,a)}{\partial E \partial a} B_S(e_S,a) \ .\end{aligned} \tag{18}$$

Thus, like in the baseline model also in case of multiplicative damages North only has an incentive to invest in adaptation in South if this reduces South equilibrium emissions. This happens if and only if in equilibrium the incentive to increase emissions due to a reduction of absolute and marginal damages (right-hand side) is outweighed by the incentive to decrease emissions by the impact adaptation investments have on the benefit and marginal benefit function (left-hand side).

6.3 Market and Non-market Damages

I now assume that both the benefit and the damage functions of North and South depend on global emissions E. This yields the following welfare functions:

$$W_N = B_N(e_N, E) - D_N(E) - a \ , \qquad W_S = B_S(e_S, E, a) - D_S(E, a) \ , \tag{19}$$

where benefit functions are decreasing and concave in global emissions E. A straight forward interpretation of this specification is to distinuish between market and non-market damages (e.g., Hoel and Sterner 2007, Sterner and Persson 2008, Traeger 2011, Drupp and Hänsel 2021). The benefit function is interpreted as the economy's aggregate production function (measured in terms of GDP). GDP production is higher, the higher are domestic emissions e_i $(i = N, S)$, yet climate change impacts also harm production, thus, the benfit functions decrease in global emissions E. The damage functions D_i $(i = N, S)$ now capture so-called non-market damages of climatic change, i.e., welfare losses that are not measured in terms of lost GDP. I further assume that $\partial^2 B_i/(\partial e_i \partial E) < 0$, i.e., marginal benefits are decreasing in global emissions.[8] Adaptation investments are now assumed to reduce South's absolute and marginal market and non-market damages:

$$\frac{\partial B_S(e_S,E,a)}{\partial a} > 0 \ , \quad \frac{\partial^2 B_S(e_S,E,a)}{\partial e_s \partial a} > 0 \ , \quad \frac{\partial D_S(E,a)}{\partial a} < 0 \ , \quad \frac{\partial^2 D_S(E,a)}{\partial E \partial a} < 0 \ . \tag{20}$$

[8] This would for example be the case if the impact of climate change on production is multiplicative, as discussed in Section 6.2. In fact, the multiplicative damage specification discussed in Section 6.2 is a special case of the more general specification discussed in this section. In terms of the welfare specifications (19), the multiplicative damage case would imply $B_i(e_i, E, \cdot) = d_i(E) b_i(e_i, \cdot)$ and $D_i(E, \cdot) = 0$ $(i = N, S)$.

Under the welfare specification (19), we obtain for the first-order conditions in the second stage (see Appendix A.8):

$$\frac{\partial B_N(e_N,E)}{\partial e_N}=\frac{\partial D_N(E)}{\partial E}-\frac{\partial B_N(e_N,E)}{\partial E}\ , \tag{21a}$$

$$\frac{\partial B_S(e_S,E,a)}{\partial e_S}=\frac{\partial D_S(E,a)}{\partial E}-\frac{B_S(e_S,E,a)}{\partial E}\ . \tag{21b}$$

Again, the first-order conditions imply that both countries choose emissions such as to equate marginal damages and marginal costs from emissions. The difference to the baseline model is that marginal damages now comprise the sum of market and non-market marginal damages. Under the assumed curvature properties there exists a unique Nash equilibrium in the second stage. In addition, emission choices are strategic substitutes.

Remark 7: In Sakamoto et al. (2020) it can happen that emission choices are strategic complements. The reason is that in terms of the welfare specification (19) they employ the following functional form:[9]

$$B_i(e_i,E,\cdot)=d_i(E)b_i(e_i,E,\cdot)\ ,\quad D_i(E,\cdot)=0\ ,\qquad i=N,S\ . \tag{22}$$

The intuition in their model is that climate change has a general detrimental effect on production, covered by the function $d_i(E)$, and, in addition, a particular detrimental effect on production.[10] In this case, the cross derivative of $B_i(e_i,E,\cdot)$ with respect to domestic emissions e_i and global emissions E may be positive, i.e., $\partial B_i(e_i,E,\cdot)/\partial e_i\partial E>0$. If, in addition, marginal damages of global emissions are almost constant, i.e., $\partial^2 D_i(E,\cdot)/\partial E^2\approx 0$ and $\partial^2 B_i(e_i,E,\cdot)/\partial E^2\approx 0$ $(i=N,S)$, then emission choices in the second stage of the game can turn into strategic complements. Unlike stated in Sakamoto et al. (2020), a necessary condition for this to happen is not a dynamic framework, but that climate damages diminish production via two separate channels.[11]

[9] In fact, Sakamoto et al. (2020) employ a dynamic framework, which cannot be directly mapped into my static model set-up. Thus, equations (22) are the "closest translation" from their dynamic framework into my static framework.

[10] The particular detrimental effect covered by $d_i(e_i,B,\cdot)$ in Sakamoto et al. (2020) is that climate damage reduces effective labor, which is an input into carbon free energy production.

[11] For Propositions 1 and 2 to hold, it does not matter whether emission choices in the second stage are strategic substitutes or complements. Yet, it matters for global emissions. If emissions choices are strategic substitutes, a reduction in equilibrium emissions of South is partly counteracted by an increase in equilibrium emissions of North (although global emissions are still decreasing). If, however, emission choices are strategic complements, a reduction of South's equilibrium emissions would also lead North to reduce its equilibrium emissions.

Turning to the first stage, the condition for North's optimal adaptation investment reads:

$$-\left(D'_N(\hat{E}(a)) - \frac{\partial B_N(\hat{e}_N, \hat{E})}{\partial E}\right) \frac{d\hat{e}_S(a)}{da} \leq 1 \ . \tag{23}$$

This is the straight forward generalization to the corresponding condition (7) in the baseline model. The only difference is that marginal benefits of adaptation investments (left-hand side) now comprise of market and non-market damages. As the term in parenthesis on the left-hand side is positive, Proposition 1 still holds: positive adaptation investments can only be optimal for North if South's equilibrium emissions decrease in adaptation investments.

Also the condition for South's equilibrium emissions to decrease of Proposition 2 generalizes in a straight forward manner:

$$\frac{d\hat{e}_S(a)}{da} < 0 \quad \Leftrightarrow \quad -\frac{\partial^2 B_S(e_S, E, a)}{\partial e_S \partial a} > -\left(\frac{\partial^2 D_S(E, a)}{\partial E \partial a} - \frac{\partial^2 B_S(e_S, E, a)}{\partial E \partial a}\right) \ . \tag{24}$$

Now South's incentive to increase equilibrium emissions due to a reduction in marginal market and non-market damages (right-hand side) has to be outweighed by the incentive to decrease equilibrium emissions due to a reduction in marginal benefits, respectively abatement costs.

6.4 Intertemporal Accumulation of GHG Emissions

In this last extension, I generalize the static baseline model to a dynamic framework. This captures that GHG emissions are a global stock pollutant, i.e., the damage from climate change is a function of cumulated emissions over space and time. To this end, I expand the second stage of the game into $T+1$ periods, with some arbitrary $T > 0$. In each of these periods $0 \leq t \leq T$ both countries simultaneously choose their domestic emission levels e_i^t $(i = N, S)$ and observe the emission choice of the other country before they chose emissions in the next period. Employing the scientific evidence that average surface temperature increase due to climate change is approximately linear to cumulated global emissions (e.g., Meinshausen et al. 2009), I assume that damages from climate change in period t depend on the stock of accumulated past emissions s^t, which develops according to the following equation of motion:

$$s^{t+1} = s^t + E^t = s^t + e_N^t + e_S^t \ , \qquad t = 0, \ldots, T-1 \ , \tag{25}$$

with some given initial stock s^0 denoting the stock of past accumulated emissions at the start of the game. Assuming a common discount factor δ employed for discounting outcomes one period ahead, the net present values of North's and South's welfare are given by:

$$W_N = \sum_{t=0}^{T} \delta^t \left[B_N^t(e_N) - D_N^t(s^t) \right] - a \ , \tag{26a}$$

$$W_S = \sum_{t=0}^{T} \delta^t \left[B_S^t(e_S, a) - D_S^t(s^t, a) \right] \ . \tag{26b}$$

Note that both benefit and damage functions are time indexed, i.e., I assume that these functions may change over time. This allows to capure technological progress and other factors changing over time. In addition, the net present value of South now depends on the discounted sum of benefits and damages. As a consequence, I do not impose that South's damages and marginal damages decrease in adaptation investment in all periods $t = 0, \ldots, T+1$ but the net present value of South's damages and marginal damages should decrease (otherwise adaptation investments do not decrease South's damages from climate change and could hardly be called adaptation investments in the first place):

$$\sum_{t=0}^{T} \delta^t \frac{\partial D_S^t(e_S^t, a)}{\partial a} < 0 \ , \qquad \sum_{t=0}^{T} \delta^t \frac{\partial^2 D_S^t(e_S^t, a)}{\partial e_S^t \partial a} < 0 \ . \tag{27}$$

Again, I assume that North adaptation investments are in the best interest of South. This implies:

$$\frac{dW_S}{da} > 0 \qquad \Leftrightarrow \qquad \sum_{t=0} \delta^t \frac{\partial B_S^t(e_S^t, a)}{\partial a} \geq \sum_{t=0}^{T} \delta^t \frac{\partial D_S^t(e_S^t, a)}{\partial a} \ . \tag{28}$$

To analyze the second stage of the game, I first employ similar definitions for South's benefit and damage functions accounting for the fact that adaptation investments $\bar{a}$ chosen by North in the first stage of the game are sunk:

$$\bar{B}_S^t(e_S^t) \equiv B_S^t(e_S^t, a)\big|_{a=\bar{a}} \ , \qquad \bar{D}_S^t(s^t) \equiv D_S^t(s^t, a)\big|_{a=\bar{a}} \ . \tag{29}$$

Second, I re-write the net present values of welfare recursively using the following Bellman equations:

$$V_N^t(s^t) = B_N^t(e_N) - D_N^t(s^t) + \delta V_N^{t+1}(s^{t+1}) \ , \tag{30a}$$

$$\bar{V}_S^t(s^t) = \bar{B}_S^t(e_S) - \bar{D}_S^t(s^t) + \delta \bar{V}_S^{t+1}(s^{t+1}) \ . \tag{30b}$$

As shown in Appendix A.9, the first-order conditions in period $t = 0, \ldots, T-1$ are given by:

$$B_N^{t\,\prime}(e_N^t) = \sum_{\tau=t+1}^{T} \delta^{\tau-t} D_N^{\tau\,\prime}(\hat{s}^\tau) \ , \quad \overline{B}_S^{t\,\prime}(e_S^t) = \sum_{\tau=t+1}^{T} \delta^{\tau-t} \overline{D}_N^{\tau\,\prime}(\hat{s}^\tau) \ , \tag{31}$$

where $\hat{s}^\tau$ denotes the accumulated stock in period $t < \tau \leq T$ in the equilibrium of the game starting in period $t+1$, which depends on the emission choices e_N^t and e_S^t in period t. Thus, marginal benefits from domestic emissions now have to equal the net present value of all future marginal damages. There exists a unique subgame perfect Nash equilibrium of the second stage of the game which is characterized by (cumulative) emissions paths $\{\hat{e}_N^t(a)\}_{t=0}^T$, $\{\hat{e}_S^t(a)\}_{t=0}^T$ and $\{\hat{s}^t(a)\}_{t=0}^T$. In every period t, emission choices of both countries are strategic substitutes.

The condition for North's optimal adaptation investment in the first stage of the game reads:

$$-\sum_{t=0}^{T-1} \left[\sum_{\tau=t+1}^{T} \delta^{\tau-t} D_N^{\tau\,\prime}(\hat{s}^\tau(a)) \right] \frac{d\hat{e}_S^t(a)}{da} \leq 1 \ . \tag{32}$$

This is the straight forward generalization of the corresponding condition (7) in the baseline model. The marginal costs of adaptation investments (right-hand side) have to equal its marginal benefits. Again, benefits can only arise from decreasing equilibrium emissions of South. The outer sum of the left-hand side sums over all of South's equilibrium emission choices. An increase in emissions in period t increases cumulative emissions from period $t+1$ onward. As a consequence, an emission increase in period t induces damages in all subsequent periods, the net present value of which is captured by the inner sum on the left-hand side.

For the left-hand side of condition (32) to be positive it is not necessary that South's emissions decrease in all periods $t = 0, \ldots, T-1$ due to increasing adaptation investments. Yet, as $D_N^{t\,\prime}(s^t) > 0$ for all $t = 0, \ldots, T$, South's emissions have to increase at least in some periods t to satisfy condition (32) with equality.

Finally, I look into the condition for South's equilibrium emissions in period t to decrease in adaptation investment a and obtain:

$$\frac{d\hat{e}_S^t(a)}{da} < 0 \quad \Leftrightarrow \quad -\frac{\partial^2 B_S^t(e_S^t, a)}{\partial e_S^t \partial a} > -\sum_{\tau=t+1}^{T} \delta^{\tau-t} \frac{\partial^2 D_S^\tau(s^\tau, a)}{\partial s^\tau \partial a} \ . \tag{33}$$

South's incentive to increase equilibrium emissions in period t stems from the decrease in marginal damages these emissions cause in the future due to higher adaptation investments (right-hand side), and has to be outweighed by South's incentive to decrease emissions because of changes in the marginal benefits due to adaptation investments (left-hand side). If the right-hand side is negative, which could happen as marginal damages could increase in adaptation investments in some periods, South's equilibrium emissions would decrease even if marginal benefits are not affected by adaptation investments. Yet, this cannot happen in all periods, as this would violate conditions (27).

In summary, the intertemporal model framework gives more flexibility in the sense that it can still be in the best interest of North to fund beneficial adaptation measures in South, even if this increases South's equilibrium emissions or marginal damages in some periods.[12] Yet, the general problem remains that the only currency in which the South can remunerate North for its adaptation investments is by reducing North's climate damages. For this to happen, South's equilibrium emissions have to go down at least in some periods and the net present value of North's welfare change due to changes in South's equilibrium emissions has to be positive.

7 Discussion and Conclusion

In the baseline model discussed in Sections 3–5, condition (8) (for the general case) and condition (10) (for the quadratic benefit function (9)) define requirements how adaptation investments of North have to influence both the benefits and damages of South such that South's domestic emissions $\hat{e}_S$ decline in equilibrium. As can be seen from the first-order condition (7) of North in the first stage, decreasing equilibrium emissions of South with respect to North's adaptation investments are a necessary condition for positive adaptation investments to be in North's best interest. As shown in Section 6, these insights carry over to various model extensions.

A potential caveat both in the baseline model and the various extensions is that I assume that North is only concerned about its own welfare. In particular, this neglects any altruistic motivations of North to fund adaptation projects in South. While I do not deny that these altruistic motives exist, I do not see any evidence that they are strong enough that rich countries would unconditionally finance adaptation measures in poor countries. If this view on current real-world affairs is correct, all my model results still hold: any altruistic motives that are not sufficiently strong to render adaptation investments in South unconditionally "profitable" for North only reduce the amount of remuneration North expects from South in return. As emission reductions are the only currency by which South can repay North

[12] Both of these effects, i.e., South's equilibrium emissions and South's marginal damages to increase in North's adaptation investment can also happen in Sakamoto et al. (2020).

for its expenses, decreasing equilibrium emissions of South remain a necessary condition for adaptation investments to be in North's best interest.

In my simplified model world, the only interaction between North and South is via the public good characteristic of GHG emissions. Yet, international trade is another important channel of cross-country interaction. In fact, Schenker and Stephan (2014) show that adaptation funding in South by North can improve North's terms of trade. Thus, improving its own position in international trade relationships constitutes another potential benefit for North to fund adaptation in South. This is supported by Bayramoglu et al. (2023), who find empirical evidence that bilateral trade relationships have a positive impact on climate aid transfers. Yet, Schenker and Stephan (2017) show in a calibrated numerical model that while international trade increases the incentives for North to finance adaptation in South, the resulting transfers fall considerably short of the aspired amount of international adaptation funding. Thus, also international trade at best mitigates North's incentive problem to finance adaptation in South and, thus, does not impair my results.

Assuming a quadratic benefit function (9), I decompose the effects of North's adaptation investments on the benefit function of the South into three different channels. First, adaptation investments can increase the fraction of GDP which is independent from GHG emissions. This upward shift in South's benefit function would increase absolute benefits while marginal benefits are unchanged. Second, adaptation investments could squeeze South's benefit function horizontally such that the maximum emission released if South's economy operates at full capacity decrease. For any level of emissions above half of maximum emissions this would increase absolute and decrease marginal benefits of South. Finally, adaptation investments could squeeze South's benefit function vertically such that for any level of emissions both absolute and marginal emissions decrease. The trick is now to find such adaptation projects that any incentive to increase equilibrium emissions due to lower absolute and marginal damages is outweighed by an incentive to decrease equilibrium emissions due to the joint impact of theses adaptation investments on South's benefit function.

While such adaptation projects surely exist, this is clearly not the general case: any "pure" adaptation projects, i.e., projects that only decrease absolute and marginal damages and have no direct or indirect influence on South's benefits always fail to be in North's best interest, as they can never satisfy (10) in the baseline model or the corresponding conditions (13), (18), (24) and (33) in the respective model extensions.

These results are important for climate policy. They indicate that adaptation investments from developed to developing countries may indeed result in a win-win situation, as described in Sakamoto et al. (2020): not only will the host countries benefit from better protection against climate change and improved production technology, but also the GHG emissions of the host countries decline, yielding benefits for the rest of the world and improving the World's chances to stay below the 2°C target. Yet, whether adaptation investments exhibit this win-win characteristic depends on the above mentioned criteria. Thus, the particular adaptation measures, into which North can invest, matter. This is an important insight that might help international adaptation funding organizations, such as the Green Climate Fund, with their selection of appropriate adaptation measures. For example, investments into large dam projects may exhibit the characteristics for condition (10), as discussed in Section 5. Another approach for international funding agencies would be to bundle mitigation and adaptation projects in such a way that the compound project is of the aforementioned win-win type.

Appendix

A.1 Existence and Uniqueness of Nash Equilibrium in Second Stage of the Game

Existence: The existence of a Nash equlibrium of the second stage of the game follows directly from the strict concavity of both countries' domestic welfare functions with respect to individual domestic emissions.

Uniqueness: From the first-order conditions (4), we obtain:

$$\hat{e}_N = B_N'^{-1}\left(D_N'(\hat{E})\right) \ , \qquad \hat{e}_S = \bar{B}_S'^{-1}\left(\bar{D}_S'(\hat{E})\right) \ . \tag{A.1}$$

The inverse functions exist, because of the strict concavity of benefit functions with respect to domestic emissions. Summing up both equations characterizes an implicit equation for the aggregate emissions $\hat{E}$ in the Nash equilibrium:

$$\hat{E} = B_N'^{-1}\left(D_N'(\hat{E})\right) + \bar{B}_S'^{-1}\left(\bar{D}_S'(\hat{E})\right) \ . \tag{A.2}$$

As the right-hand side is increasing and the left-hand side is decreasing in aggregate emissions $\hat{E}$, there exists a unique equilibrium level $\hat{E}$ of aggregate emissions. Inserting back $\hat{E}$ into equations (A.1) yields the unique levels of domestic emissions $\hat{e}_N$ and $\hat{e}_S$ in the Nash equilibrium of the second stage of the game.

In addition, we obatin:

$$\frac{d\hat{e}_N}{de_S} = \frac{D_N''}{B_N'' - D_N''} \leq 0 \ , \qquad \frac{d\hat{e}_S}{de_N} = \frac{\bar{D}_S''}{\bar{B}_S'' - \bar{D}_S''} \leq 0 \ . \tag{A.3}$$

Thus, emission choices of North and South in the second stage of the game are always strategic substitutes (or dominant strategies if $D_i'' = 0$).

A.2 Optimal Adaptation Investment Choice in First Stage of the Game

The North maximizes own domestic welfare (5) with respect to adaptation investments under the constraint that adaptation investments must not be negative. The first and second derivative of (5) with respect to adaptation investments read:

$$FOC \equiv \frac{dW_N}{da} = B_N'\big(\hat{e}_N(a)\big)\frac{d\hat{e}_N(a)}{da} - D_N'\big(\hat{E}(a)\big)\frac{d\hat{E}(a)}{da} - 1 \leq 0 \ , \tag{A.4a}$$

$$\begin{aligned} SOC \equiv \frac{dFOC}{da} &= B_N''\big(\hat{e}_N(a)\big)\left(\frac{d\hat{e}_N(a)}{da}\right)^2 - B_N'\big(\hat{e}_N(a)\big)\frac{d^2\hat{e}_N(a)}{da^2} \\ &\quad - D_N''\big(\hat{E}(a)\big)\left(\frac{d\hat{E}(a)}{da}\right)^2 - D_N'\big(\hat{E}(a)\big)\frac{d^2\hat{E}(a)}{da^2} \ . \end{aligned} \tag{A.4b}$$

Note that $B'_N\big(\hat{e}_N(a)\big) = D'_N\big(\hat{E}_N(a)\big)$ because of the first order condition (4) of the second stage and that $\hat{E} = \hat{e}_N + \hat{e}_s$. As a consequence, we can write

$$FOC = -D'_N\big(\hat{E}(a)\big)\frac{d\hat{e}_S(a)}{da} - 1 \leq 0 \ , \tag{A.5a}$$

$$SOC = B''_N\big(\hat{e}_N(a)\big)\left(\frac{d\hat{e}_N(a)}{da}\right)^2 - D''_N\big(\hat{E}(a)\big)\left(\frac{d\hat{E}(a)}{da}\right)^2 - D'_N\big(\hat{E}(a)\big)\frac{d^2\hat{e}_S(a)}{da^2} \tag{A.5b}$$

Thus, a sufficient condition for the second-order condition $SOC < 0$ to hold is that second stage equilibrium emissions of the South are concave in North's adaptation investments.

A.3 Proof of Proposition 1

As $D'_N(E) > 0$ by assumption, the left-hand side of condition (A.3) is positive if and only if South's equilibrium emissions decrease in adaptation investments a, i.e., $d\hat{e}_S/da < 0$. Thus condition (A.3) can only hold with equality if $d\hat{e}_S/da < 0$, as the right-hand side of condition (A.3) is always positive and equal to one.

A.4 Proof of Proposition 2

To elicit how domestic emissions in the Nash equilibrium of the second stage change with respect to adaptation investments of the North in the first stage, we totally differentiate the first-order conditions (4) of the second stage of North and South:

$$0 = B''_N d\hat{e}_N - D''_N(d\hat{e}_N + d\hat{e}_S) \ , \tag{A.6a}$$

$$0 = \bar{B}''_S d\hat{e}_S - \bar{D}''_S(d\hat{e}_N + d\hat{e}_S) + \left(\frac{\partial \bar{B}'_S}{\partial a} + \frac{\partial \bar{D}'_S}{\partial a}\right) da \ . \tag{A.6b}$$

Solving for $d\hat{e}_S(a)/da$ yields:

$$\frac{d\hat{e}_S(a)}{da} = \frac{D''_N - B''_N}{\bar{B}''_S B''_N - \bar{B}''_S D''_N - B''_N \bar{D}''_S}\left(\frac{\partial B'_S}{\partial a} - \frac{\partial \bar{D}'_S}{\partial a}\right) \ . \tag{A.7}$$

As the fraction is always strictly positive, $\hat{e}_S(a)/da < 0$ if and only if the term in parentheses is negative, which is equivalent to condition (8).

A.5 Condition (8) for quadratic benefit function

For the quadratic benefit function (9), we obtain:

$$\frac{\partial B_S(e_s, a)}{\partial e_S} = \frac{2\alpha(a)}{\beta(a)^2}\left[\beta(a) - e_s\right] \ , \qquad \frac{\partial^2 B_S(e_S, a)}{\partial e_s^2} = -\frac{2\alpha(a)}{\beta(a)^2} \ . \tag{A.8}$$

Thus, $B_S(e_S, a)$ exhibits its maximum $\alpha(a)$ at the domestic emission level $e_s = \beta(a)$. Differentiating $\partial B_S(e_s, a)/\partial e_S$ with respect to adaptation investments a yields:

$$\frac{\partial^2 B_S(e_S, a)}{\partial e_S \partial a} = -\frac{2\alpha(a)}{\beta(a)^2} \left\{ \left[2\hat{e}_S - \beta(a)\right] \frac{\beta'(a)}{\beta(a)} + \left[\beta(a) - \hat{e}_S\right] \frac{\alpha'(a)}{\alpha(a)} \right\} \ . \tag{A.9}$$

Inserting into condition (8) of Proposition 2, we derive (10).

A.6 Adaptation Investments also Affect North's Benefit Function

In case that North benefits also depend on adaptation investments, i.e., $B_N = B_N(e_N, a)$, we can define the following abbreviation analogously to definitions (3):

$$\bar{B}_N(e_N) \equiv B_N(e_N, a)\big|_{a=\bar{a}} \ , \tag{A.10}$$

for some given level of adaptation investment $\bar{a}$ chosen in the first-stage of the game. Then, the first-order conditions of the second stage read:

$$\bar{B}_N'(e_N) = D_N'(E) \ , \qquad \bar{B}_S'(e_S) = \bar{D}_S'(E) \ . \tag{A.11}$$

Following the analogous procedure detailed in Appendix A.1 reveals that conditions (4) characterize the unique Nash equilibrium of the second stage of the game. Totally differentiating the first-order conditions with respect to second stage emissions choices, we obtain that emission choices are strategic substitutes:

$$\frac{de_N}{de_S} = \frac{D_N''}{\bar{B}_N'' - D_N''} \leq 0 \ , \qquad \frac{de_S}{de_N} = \frac{\bar{D}_S''}{\bar{B}_S'' - \bar{D}_S''} \leq 0 \ . \tag{A.12}$$

In the first stage of the game, North anticipates the second stage equilibrium emissions $\hat{e}_N(a)$, $\hat{e}_S(a)$ and $\hat{E}(a)$. Thus, North welfare in the first-stage can be written as:

$$W_N(a) = B_N\big(\hat{e}_N(a), a\big) - D_N\big(\hat{E}(a)\big) - a \ . \tag{A.13}$$

Maximizing (A.13) with respect to adaptation investments yields

$$\frac{\partial B_N\big(\hat{e}_N(a), a\big)}{\partial a} + \frac{\partial B_N\big(\hat{e}_N(a), a\big)}{\partial e_N} \frac{d\hat{e}_N(a)}{da} - D_N'\big(\hat{E}(a)\big) \frac{d\hat{E}(a)}{da} - 1 \leq 0 \ , \tag{A.14}$$

which can be simplified to condition (11) by taking the first order conditions (4) into account.

Totally differentiating the first-order conditions (A.11) with respect to emission choices and adaptation investments yields:

$$0 = \bar{B}_N'' d\hat{e}_N - D_N''(d\hat{e}_N + d\hat{e}_S) + \frac{\partial \bar{B}_N'}{\partial a} da \ , \tag{A.15a}$$

$$0 = \bar{B}_S'' d\hat{e}_S - \bar{D}_S''(d\hat{e}_N + d\hat{e}_S) + \left(\frac{\partial \bar{B}_S'}{\partial a} + \frac{\partial \bar{D}_S'}{\partial a} \right) da \ . \tag{A.15b}$$

Solving for $d\hat{e}_S(a)/da$ yields:

$$\frac{d\hat{e}_S(a)}{da} = \frac{\left(D_N'' - \bar{B}_N''\right)\left(\frac{\partial B_S'}{\partial a} - \frac{\partial \bar{D}_S'}{\partial a}\right) - \bar{D}_S'' \frac{\partial \bar{B}_N'}{\partial a}}{\bar{B}_S'' \bar{B}_N'' - \bar{B}_S'' D_N'' - \bar{B}_N'' \bar{D}_S''} \ . \tag{A.16}$$

As the denominator is always positive, the numerator determines the sign of $\hat{e}_S(a)/da$. Re-arranging yields condition (13).

A.7 Multiplicative Damages

In case of multiplicative damages, as defined in equations (14), the first order conditions of the second stage of the game read:

$$B_N'(e_N) D_N(E) + B_N(e_N) D_N'(E) = 0 \ , \quad \bar{B}_S'(e_S) \bar{D}_S(E) + \bar{B}_S(e_S) \bar{D}_S'(E) = 0 \ . \tag{A.17}$$

Existence of a Nash equilibrium in the second stage of the game follows directly from the strict concavity of the countries' welfare functions:

$$B_N''(e_N) D_N(E) + 2B_N'(e_N) D_N'(E) + B_N(e_N) D_N''(E) < 0 \ , \tag{A.18a}$$

$$\bar{B}_S''(e_S) \bar{D}_S(E) + 2\bar{B}_S'(e_S) \bar{D}_S'(E) + \bar{B}_S(e_S) \bar{D}_S''(E) < 0 \ . \tag{A.18b}$$

To show uniqueness, we re-write the first-order conditions to yield:

$$\hat{e}_N = \left(\frac{B_N'}{B_N} \right)^{-1} \left(\frac{D_N'(\hat{E})}{D_N(\hat{E})} \right) \ , \qquad \hat{e}_S = \left(\frac{\bar{B}_S'}{\bar{B}_S} \right)^{-1} \left(\frac{\bar{D}_S'(\hat{E})}{\bar{D}_S(\hat{E})} \right) \ . \tag{A.19}$$

The inverse functions exist, because B_i'/B_i $(i = N, S)$ are monotonously decreasing functions with respect to domestic emissions. Summing up both equations characterizes an implicit equation for the aggregate emissions $\hat{E}$ in the Nash equilibrium:

$$\hat{E} = \left(\frac{B_N'}{B_N} \right)^{-1} \left(\frac{D_N'(\hat{E})}{D_N(\hat{E})} \right) + \left(\frac{\bar{B}_S'}{\bar{B}_S} \right)^{-1} \left(\frac{\bar{D}_S'(\hat{E})}{\bar{D}_S(\hat{E})} \right) \ . \tag{A.20}$$

As the right-hand side is increasing and the left-hand side is decreasing in aggregate emissions $\hat{E}$, there exists a unique equilibrium level $\hat{E}$ of aggregate emissions. Again, equilibrium emission choices in the second stage of the game are strategic substitutes:

$$\frac{d\hat{e}_N}{de_S} = -\frac{B'_N D'_N + B_N D''_N}{B''_N D_N + 2B'_N D'_N + B_N D''_N} < 0 \ , \quad \frac{d\hat{e}_S}{de_N} = -\frac{\bar{B}'_S \bar{D}'_S + \bar{B}_S \bar{D}''_S}{\bar{B}''_S \bar{D}_S + 2\bar{B}'_S \bar{D}'_S + \bar{B}_S \bar{D}''_S} < 0 \ . \quad \text{(A.21)}$$

In the first stage of the game, North anticipates the second stage equilibrium emissions $\hat{e}_N(a)$, $\hat{e}_S(a)$ and $\hat{E}(a)$. Thus, North welfare in the first-stage can be written as:

$$W_N(a) = D_N\big(\hat{E}(a)\big) B_N\big(\hat{e}_N(a), a\big) - a \ . \tag{A.22}$$

Maximizing (A.22) with respect to adaptation investments yields

$$D'_N\big(\hat{E}(a)\big) B_N\big(\hat{e}_N(a)\big) \frac{d\hat{E}(a)}{da} + D_N\big(\hat{E}(a)\big) B'_N\big(\hat{e}_N(a)\big) \frac{d\hat{e}_N(a)}{da} - 1 \leq 0 \ , \tag{A.23}$$

which can be simplified to condition (17) by taking the first order conditions (A.17) into account.

Totally differentiating the first-order conditions (A.17) with respect to emission choices and adaptation investments yields:

$$0 = (D_N B''_N + D'_N B'_N)\, d\hat{e}_N - (D'_N B'_N + D''_N B_N)\,(d\hat{e}_N + d\hat{e}_S) \ , \tag{A.24a}$$

$$\begin{aligned} 0 &= \big(\bar{D}_S \bar{B}''_S + \bar{D}'_S \bar{B}'_S\big)\, d\hat{e}_S - \big(\bar{D}'_S \bar{B}'_S + \bar{D}''_S \bar{B}_S\big)\,(d\hat{e}_N + d\hat{e}_S) \\ &\quad + \left(\frac{\partial \bar{D}_S}{\partial a} \bar{B}'_S + \bar{D}_S \frac{\partial \bar{B}'_S}{\partial a} + \frac{\partial \bar{D}'_S}{\partial a} \bar{B}_S + \bar{D}'_S \frac{\partial \bar{B}_S}{\partial a}\right) da \ . \end{aligned} \tag{A.24b}$$

Solving for $d\hat{e}_S(a)/da$ yields:

$$\frac{d\hat{e}_S(a)}{da} = \frac{\frac{\partial \bar{D}_S}{\partial a} \bar{B}'_S + \bar{D}_S \frac{\partial \bar{B}'_S}{\partial a} + \frac{\partial \bar{D}'_S}{\partial a} \bar{B}_S + \bar{D}'_S \frac{\partial \bar{B}_S}{\partial a}}{\big(\bar{D}'_S \bar{B}'_S + \bar{D}''_S \bar{B}_S\big)\,(D'_N B'_N + D''_N B_N) - \bar{D}_S \bar{B}''_S - \bar{D}'_S \bar{B}'_S \bar{B}''_N} \ . \tag{A.25}$$

As the denominator is always positive, the numerator determines the sign of $\hat{e}_S(a)/da$. Re-arranging yields condition (18).

A.8 Market and Non-market Damages

In case of the specification accounting for market and non-market damages, as defined in equations (19), the first order conditions of the second stage of the game read:

$$\frac{\partial B_N(e_N, E)}{\partial e_N} + \frac{\partial B_N(e_N, E)}{\partial E} - D'_N(E) = 0 \ , \tag{A.26a}$$

$$\frac{\partial B_S(e_S, E, a)}{\partial e_S} + \frac{\partial B_S(e_S, E, a)}{\partial E} - \frac{\partial D_S(E, a)}{\partial E} = 0 \ . \tag{A.26b}$$

Existence of a Nash equilibrium in the second stage of the game follows directly from the strict concavity of the countries' welfare functions:

$$\frac{\partial^2 B_N(e_N,E)}{\partial e_N^2} + 2\frac{\partial^2 B_N(e_N,E)}{\partial e_N \partial E} + \frac{\partial^2 B_N(e_N,E)}{\partial E^2} - D_N''(E) < 0 \ , \tag{A.27a}$$

$$\frac{\partial^2 B_S(e_S,E,a)}{\partial e_S^2} + 2\frac{\partial^2 B_S(e_S,E,a)}{\partial e_S \partial E} + \frac{\partial^2 B_S(e_S,E,a)}{\partial E^2} - \frac{\partial^2 D_S(E,a)}{\partial E^2} < 0 \ . \tag{A.27b}$$

To show uniqueness, we re-write the first-order conditions to yield:

$$\hat{e}_N = \left(\frac{\partial B_N}{\partial e_N}\right)^{-1}\left(\frac{\partial D_N}{\partial E} - \frac{\partial B_N}{\partial E}\right) \ , \qquad \hat{e}_S = \left(\frac{\partial B_S}{\partial e_S}\right)^{-1}\left(\frac{\partial D_S}{\partial E} - \frac{\partial B_S}{\partial E}\right) \ . \tag{A.28}$$

The inverse functions exist, because the benefit functions are strictly concave with respect to domestic emissions. Summing up both equations characterizes an implicit equation for the aggregate emissions $\hat{E}$ in the Nash equilibrium:

$$\hat{E} = \left(\frac{\partial B_N}{\partial e_N}\right)^{-1}\left(\frac{\partial D_N}{\partial E} - \frac{\partial B_N}{\partial E}\right) + \left(\frac{\partial B_S}{\partial e_S}\right)^{-1}\left(\frac{\partial D_S}{\partial E} - \frac{\partial B_S}{\partial E}\right) \ . \tag{A.29}$$

As the right-hand side is increasing and the left-hand side is decreasing in aggregate emissions $\hat{E}$, there exists a unique equilibrium level $\hat{E}$ of aggregate emissions. Again, equilibrium emission choices in the second stage of the game are strategic substitutes:

$$\frac{d\hat{e}_N}{de_S} = -\frac{\frac{\partial^2 B_N}{\partial E^2} + \frac{\partial^2 B_N}{\partial e_N \partial E} - D_N''}{\frac{\partial^2 B_N}{\partial e_N^2} + 2\frac{\partial^2 B_N}{\partial e_N \partial E} + \frac{\partial^2 B_N}{\partial E^2} - D_N''} < 0 \ , \quad \frac{d\hat{e}_S}{de_N} = -\frac{\frac{\partial^2 B_S}{\partial E^2} + \frac{\partial^2 B_S}{\partial e_S \partial E} - \frac{\partial^2 D_S}{\partial E^2}}{\frac{\partial^2 B_S}{\partial e_S^2} + 2\frac{\partial^2 B_S}{\partial e_S \partial E} + \frac{\partial^2 B_S}{\partial E^2} - \frac{\partial^2 D_S}{\partial E^2}} < 0 \ . \tag{A.30}$$

Note that this result hinges on the assumption that $\partial^2 B_i/(\partial e_i \partial E) < 0$. If one relaxes this assumption, emission choices may turn out to be strategic complements (see Remark 7).

In the first stage of the game, North anticipates the second stage equilibrium emissions $\hat{e}_N(a)$, $\hat{e}_S(a)$ and $\hat{E}(a)$. Thus, North welfare in the first-stage can be written as:

$$W_N(a) = B_N\big(\hat{e}_N(a), \hat{E}(a)\big) - D_N\big(\hat{E}(a)\big) - a \ . \tag{A.31}$$

Maximizing (A.31) with respect to adaptation investments yields

$$\frac{\partial B_N\big(\hat{e}_N(a),\hat{E}(a)\big)}{\partial e_N}\frac{d\hat{e}_N(a)}{da} + \frac{\partial B_N\big(\hat{e}_N(a),\hat{E}(a)\big)}{\partial E}\frac{d\hat{E}(a)}{da} - D_N'\big(\hat{E}(a)\big)\frac{d\hat{E}(a)}{da} - 1 \leq 0 \ , \tag{A.32}$$

which can be simplified to condition (23) by taking the first order conditions (A.26) into account.

Totally differentiating the first-order conditions (A.17) with respect to emission choices and adaptation investments yields:

$$0 = \left(\frac{\partial^2 B_N}{\partial e_N^2} + \frac{\partial^2 B_N}{\partial e_N \partial E}\right) d\hat{e}_N - \left(\frac{\partial^2 B_N}{\partial E^2} + \frac{\partial^2 B_N}{\partial e_N \partial E} - D_N''\right)(d\hat{e}_N + d\hat{e}_S) \ , \tag{A.33a}$$

$$\begin{aligned} 0 = &\left(\frac{\partial^2 B_S}{\partial e_S^2} + \frac{\partial^2 B_S}{\partial e_S \partial E}\right) d\hat{e}_S - \left(\frac{\partial^2 B_S}{\partial E^2} + \frac{\partial^2 B_S}{\partial e_S \partial E}\right)(d\hat{e}_N + d\hat{e}_S) \\ &+ \left(\frac{\partial^2 B_S}{\partial e_S \partial a} + \frac{\partial^2 B_S}{\partial E \partial a} - \frac{\partial^2 D_S}{\partial E \partial a}\right) da \ . \end{aligned} \tag{A.33b}$$

Solving for $d\hat{e}_S(a)/da$ yields:

$$\frac{d\hat{e}_S(a)}{da} = N\left(\frac{\partial^2 B_S}{\partial e_S \partial a} + \frac{\partial^2 B_S}{\partial E \partial a} - \frac{\partial^2 D_S}{\partial E \partial a}\right) \ , \tag{A.34}$$

where N is given by:

$$\frac{D_N'' - \frac{\partial^2 B_N}{\partial e_N^2} - 2\frac{\partial^2 B_N}{\partial e_N \partial E} - \frac{\partial^2 B_N}{\partial E^2}}{\left(\frac{\partial^2 B_S}{\partial e_S^2} + \frac{\partial^2 B_S}{\partial e_S \partial E}\right)\left(\frac{\partial^2 B_N}{\partial e_N^2} + 2\frac{\partial^2 B_N}{\partial e_N \partial E} + \frac{\partial^2 B_N}{\partial E^2} - D_N''\right) + \left(\frac{\partial^2 B_S}{\partial e_S \partial E} + \frac{\partial^2 B_S}{\partial E^2} - \frac{\partial^2 D_S}{\partial E^2}\right)\left(\frac{\partial^2 B_N}{\partial e_N^2} + \frac{\partial^2 B_N}{\partial e_N \partial E}\right)} \ . \tag{A.35}$$

As $N > 0$, the sign of $\hat{e}_S(a)/da$ is determined by the term in parentheses. Re-arranging yields condition (24).

A.9 Intertemporal Accumulation of GHG

Employing the recursive formulation of welfare (30), the first-order conditions for any period $0 \leq t \leq T$ in the second stage of the game read:

$$B_N^{t\,\prime}(e_N^t) + \delta V_N^{t+1\prime}(s^{t+1}) = 0 \ , \qquad \overline{B}_S^{t\,\prime}(e_S^t) + \delta \overline{V}_S^{t+1\prime}(s^{t+1}) = 0 \ . \tag{A.36}$$

A sufficient condition for the second-order conditions to be satisfied is that $V_i^{t+1\prime\prime}(s^{t+1}) < 0$ ($i = N, S$):

$$B_N^{t\,\prime\prime}(e_N^t) + \delta V_N^{t+1\prime\prime}(s^{t+1}) < 0 \ , \qquad \overline{B}_S^{t\,\prime\prime}(e_S^t) + \delta \overline{V}_S^{t+1\prime\prime}(s^{t+1}) = 0 \ . \tag{A.37}$$

In addition, from the envelope theorem follows:

$$V_N^{t\,\prime}(s^t) = -D_N^{t\,\prime}(s^t) + \delta V_N^{t+1\prime}(s^{t+1}) \ , \qquad \overline{V}_S^{t\,\prime}(s^t) = -\overline{D}_S^{t\,\prime}(s^t) + \delta \overline{V}_S^{t+1\prime}(s^{t+1}) \ . \tag{A.38}$$

We show that there exist a unique subgame perfect Nash equilibrium of the second stage of the game by backward induction.

First, consider period $t = T$. The second-order condition holds, because $V_i^{T+1} \equiv 0$ ($i = N, S$), as the model world ends after period T. In addition, the first-order conditions yield:

$$B_N^{T\prime}(e_N^T) = 0 \ , \qquad \overline{B}_S^{T\prime}(e_S^T) = 0 \ . \tag{A.39}$$

This implies that $\hat{e}_N^T = \epsilon_N^T$ and $\hat{e}_S^T = \epsilon_S^T$, where ϵ_N^T and ϵ_S^T denote the maximum emissions in period T that North, respectively South emit if they run their economy at full capacity. From the envelope theorem we obtain:

$$V_N^{T\prime}(s^T) = -D_N^T(s^T) \quad \Rightarrow \quad V_N^{T\prime\prime} = -D_N^{T\prime\prime}(s^T) < 0 \ , \tag{A.40a}$$
$$\overline{V}_S^{T\prime}(s^T) = -\overline{D}_S^T(s^T) \quad \Rightarrow \quad \overline{V}_S^{T\prime\prime} = -\overline{D}_S^{T\prime\prime}(s^T) < 0 \ . \tag{A.40b}$$

This ensures that the second order conditions in period $T-1$ hold.

Second, assume that there exists a unique subgame perfect Nash equilibrium for subgame starting in period $t+1$ $(0 \leq t \leq T-1)$ and that $V_i^{t+1\prime\prime} < 0$ for $i = N, S$. Then the second order condition for period t holds and emission choices in period t are implicitly given by the first-order conditions (A.36), which can be re-arranged to yield:

$$\hat{e}_N^t = \left(B_N^{t\,\prime}\right)^{-1}\left(\delta V_N^{t+1\prime}(s^t + \hat{E}^t)\right) \ , \qquad \hat{e}_S^t = \left(\overline{B}_S^{t\,\prime}\right)^{-1}\left(\delta \overline{V}_S^{t+1\prime}(s^t + \hat{E}^t)\right) \ . \tag{A.41}$$

Again, the inverse functions exist as the benefit fucntions are strictly concave. Summing-up over both countries, we obtain:

$$\hat{E}^t = \left(B_N^{t\,\prime}\right)^{-1}\left(\delta V_N^{t+1\prime}(s^t + \hat{E}^t)\right) + \left(\overline{B}_S^{t\,\prime}\right)^{-1}\left(\delta \overline{V}_S^{t+1\prime}(s^t + \hat{E}^t)\right) \ . \tag{A.42}$$

As the left-hand side is increasing and the right-hand side decreasing in $\hat{E}$ there exist unique equilibrium emissions $\hat{E}^t$ for any given stock of cumulative emissions s^t. In addition, emission choices in period t are strategic substitutes:

$$\frac{\hat{e}_N^t}{de_S^t} = -\frac{\delta V_N^{t+1\prime\prime}}{B_N^{t\,\prime\prime} + \delta V_N^{t+1\prime\prime}} < 0 \ , \qquad \frac{\hat{e}_S^t}{de_N^t} = -\frac{\delta \overline{V}_S^{t+1\prime\prime}}{\overline{B}_S^{t\,\prime\prime} + \delta \overline{V}_S^{t+1\prime\prime}} < 0 \ . \tag{A.43}$$

Finally, we have to show that $V_i^{t\prime\prime} < 0$ for $i = N, S$. Differentiating equations (A.38) with respect to s^t yields:

$$V_N^{t\,\prime\prime}(s^t) = -D_N^{t\,\prime\prime}(s^t) + \delta V_N^{t+1\prime\prime}(s^{t+1})\frac{ds^{t+1}}{s^t} \ , \quad \overline{V}_S^{t\,\prime\prime}(s^t) = -\overline{D}_S^{t\,\prime\prime}(s^t) + \delta \overline{V}_S^{t+1\prime\prime}(s^{t+1})\frac{ds^{t+1}}{s^t} \ . \tag{A.44}$$

As $s^{t+1} = s^t + \hat{E}^t$, we obtain:

$$\frac{ds^{t+1}}{ds^t} = 1 + \frac{d\hat{E}^t}{ds^t} \ . \tag{A.45}$$

Using the implicit function theorem on equation (A.42) we obtain:

$$\frac{d\hat{E}^t}{ds^t} = -\frac{\delta\left(B_N^t{}''\overline{V}_S^{t+1}{}'' + \overline{B}_S^t{}''V_N^{t+1}{}''\right)}{B_N^t{}''\overline{B}_S^t{}'' + \delta\left(B_N^t{}''\overline{V}_S^{t+1}{}'' + \overline{B}_S^t{}''V_N^{t+1}{}''\right)} \in [-1,0] \ . \tag{A.46}$$

And, thus, $ds^{t+1}/ds^t > 0$ and $V_i^{t}{}'' < 0$ for $i = N, S$. Working recursively from $t = T$ to $t = 0$ characterizes the unique Nash equilibrium of the second stage of the game characterized by emission paths $\{\hat{e}_N^t(a)\}_{t=0}^{T+1}$, $\{\hat{e}_S^t(a)\}_{t=0}^{T+1}$ and $\{\hat{s}^t(a)\}_{t=0}^{T+1}$.

In the first stage of the game, North's welfare reads:

$$W_N = V_N^0(s^0) - a \ . \tag{A.47}$$

Maximizing North's welfare with respect to adaptation investments a yields the following first-order condition:

$$\frac{dV_N^0(s^0)}{da} \leq 0 \ . \tag{A.48}$$

For any time period $0 \leq t \leq T$, the following relationship holds:

$$\begin{aligned}\frac{dV_N^t(s^t)}{da} &= B_N^t{}'\big(\hat{e}_N^t\big)\frac{d\hat{e}_N^t}{da} + \delta V_N^{t+1}{}'\big(s^t+\hat{E}^t\big)\frac{d\hat{E}^t}{da} + \delta\frac{V_N^{t+1}(s^{t+1})}{da}\\ &= \underbrace{\left[B_N^t{}'\big(\hat{e}^t\big) + \delta V_N^{t+1}{}'\big(s^t+\hat{E}^t\big)\right]}_{\equiv 0 \text{ (second stage FOC)}}\frac{d\hat{e}_N^t}{da} + \delta V_N^{t+1}{}'\big(s^t+\hat{E}^t\big)\frac{d\hat{e}_S^t}{da} + \delta\frac{V_N^{t+1}(s^{t+1})}{da}\\ &= \delta V_N^{t+1}{}'\big(s^t+\hat{E}^t\big)\frac{d\hat{e}_S^t}{da} + \delta\frac{V_N^{t+1}(s^{t+1})}{da} \ .\end{aligned} \tag{A.49}$$

Thus, by induction, we obtain:

$$\frac{dV_N^0(s^0)}{da} = \sum_{t=0}^{T-1}\delta V_N^{t+1}{}'(s^{t+1})\frac{d\hat{e}_S^t}{da} \ . \tag{A.50}$$

In addition, by induction equation (A.38) yields:

$$V_N^t{}'(s^t) = -\sum_{\tau=t+1}^{T}\delta^{\tau-t}D_N^\tau{}'(s^\tau) \ . \tag{A.51}$$

Together, the first-order condition of the first stage of the game reads:

$$-\sum_{t=0}^{T}-1\left[\sum_{\tau=t+1}^{T}\delta^{\tau-t}D_N^\tau{}'(s^\tau)\right]\frac{d\hat{e}_S^t}{da} \leq 0 \ . \tag{A.52}$$

Totally differentiating the first-order conditions (A.36) with respect to emission choices in period t

$$0 = B_N^{t\,\prime\prime} d\hat{e}_N + \delta V_N^{t+1\prime\prime}(d\hat{e}_N + d\hat{e}_S)\ , \tag{A.53a}$$

$$0 = \overline{B}_S^{t\,\prime\prime} d\hat{e}_N + \delta \overline{V}_S^{t+1\prime\prime}(d\hat{e}_N + d\hat{e}_S) + \left(\frac{\partial \overline{B}_S^{t\,\prime}}{\partial a} + \delta \frac{d\overline{V}_S^{t+1\prime}}{\partial a}\right) da\ . \tag{A.53b}$$

Solving for $d\hat{e}_S(a)/da$ yields:

$$\frac{d\hat{e}_S(a)}{da} = \frac{-B_N^{t\,\prime\prime} - \delta V_N^{t+1\prime\prime}}{B_N^{t\,\prime\prime}\overline{B}_S^{t\,\prime\prime} + \delta\left(B_N^{t\,\prime\prime}\overline{V}_S^{t+1\prime\prime} + \overline{B}_S^{t\,\prime\prime} V_N^{t+1\prime\prime}\right)} \left(\frac{\partial \overline{B}_S^{t\,\prime}}{\partial a} + \delta \frac{d\overline{V}_S^{t+1\prime}}{\partial a}\right)\ . \tag{A.54}$$

As the fraction is always positive, the sign of $d\hat{e}_S(a)/da$ is given by the term in parentheses. Employing equations (A.51) and (A.52) yields condition (33).

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