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Global Climate Change and the Funding of Adaptation

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Abstract

Mitigation and adaptation are the most important strategies in combating global climate change. It is expected that in a post Kyoto world industrialized countries have to engage in greenhouse gas abatement, and to support developing countries in adapting to climate change. Within the framework of a non-cooperative Nash game we analyze, whether funding adaptation is incentive compatible in the sense that it stipulates mitigation. In particular it is the aim of this paper to discuss: (1) How does foreign funding of adaptation affect mitigation and regional welfare? (2) Under which conditions is it economically rational to fund adaptation in developing regions? We find that, if strict complementarity between adaptation and mitigation exists, funding adaptation increases both global mitigation and the donors' welfare, but negatively affects the recipients' welfare. The later only benefit, if maladaptation or adaptation, which is neutral to mitigation, is funded, which, however, makes the donors worse off.

JEL-classification: C72, F51, Q54

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1 Introduction

Without any doubt, the Kyoto Protocol is an important step in combating global climate change. Nonetheless, it is relatively ineffective in achieving the long-term goals as fixed in the United Nations Framework Convention on Climate Change (UNFCCC). A major reason is that the reduction targets set in the Protocol are too low, and that most of the developing countries as well as the fast growing regions of Asia and Latin America are exempted from the duty of greenhouse gas abatement. However, because of the inertia of the climate system, even more radical reduction targets would not significantly slow down the rate of global warming over the next decade. Consequently, mitigation, which refers to all kinds of efforts for limiting greenhouse gas emissions, cannot be the only policy response to the threat of global climate change. Alternatively, there exists the possibility to reduce a region's vulnerability to the undesired impacts of global warming by adapting the human society to a changing climate. Thereby, adaptation can cover a wide range of different measures. Examples are among others early warning systems, investments into coastal and flood protection or the planting of drought-resistant crops (e.g. Smit et al., 2000).

How vulnerable a society is and might be in the future depends on its exposure to climate risk and its capacity to adapt, which is a function of societies' institutions, the level of education and economic wealth (see Adger et al., 2003). Unfortunately, the impacts of global climate change are unevenly distributed among regions, and the societies, which are most heavily exposed to climate impacts and which will suffer first, are the ones, which are the least able to bear the costs, and which are the least responsible for global warming (e.g. Stern et. al, 2006). This was acknowledged at the 2001 Climate Change Convention (COP6) meeting, where it was agreed to establish three funds for supporting adaptation in the developing world: (1) the Least Developed Countries Fund, which aims at supporting the 49 least developed countries, (2) the Special Climate Change Fund, which provides financial support to all developing countries, and (3) the Adaptation Fund, which is based on Article 12 of the Kyoto Protocol (e.g. Burton et al., 2006).[1]

Although there is general agreement that adaptation is important in combating global climate change, there are doubts about the benefits of funding adaptation.

[1] The Adaptation Fund was finalized at the last United Nations Climate Conference 2007 (COP13) in Bali. Additionally, several OECD countries, like the United States, Great Britain, Japan and Germany have supported more than 50 adaptation projects in more than 29 countries.

First, especially the poorest among the developing countries suffer from institutional and structural deficits, and hence are not very attractive for funding by the private sector (see Agarwal et al., 1999). In this context Banuri and Gupta (2000) argue that the Clean Development Mechanism might follow the path of foreign direct investment, where mainly the larger developing countries and not the poorest, small ones benefit. Second, these funds are voluntary, they are poorly funded, and they are managed by the Global Environmental Facility, on which the developing countries put little confidence (see Najan et al., 2003).

Efficiency and effectiveness are important aspects to consider. But equally important is the issue of participation and compliance in greenhouse gas mitigation (see Barnet and Stavins, 2003). Unquestionably, for achieving the long-term goals as stated in Articles 2 and 3 by the UNFCCC, all counties, both the industrialized and the developing ones, must actively curb greenhouse gas emissions (e.g. Najam et al., 2003). Therefore, the developing countries, which so far have kept aside of global climate conventions, should take over responsibility and share the duties of greenhouse gas mitigation. This immediately leads to a question, which is in the center of the present analysis: Can funding adaptation be incentive compatible in the sense that it induces engagement in greenhouse gas mitigation of both the industrialized and developing regions?

To be more precise, it is not the aim of this paper to analyze the adaptation fund as defined in the Kyoto Protocol. We focus on a situation like for example the post Kyoto period, where countries are engaged in greenhouse gas abatement on the one hand, and where industrialized countries can support developing countries in adapting to climate change on the other. In particular, we intend to answer the questions: Do industrialized countries have an incentive to finance adaptation in developing countries? Does funding adaptation improve the welfare of both the industrial and developing countries? How does funding adaptation affect mitigation by developing countries and how does it affect global mitigation?

From an economic perspective a major difference exists between adaptation and mitigation. Adaptation generates benefits, which are typically private and regional, whereas benefits from mitigation are public and global. Therefore, economic rationality seems to suggest that without international arrangements for abatement and burden-sharing industrialized countries have no incentive to voluntarily invest into foreign adaptation infrastructures. If funding were an issue at all, then one would expect that from the industrialized countries' perspective funding mitigation in developing countries combined with investing in own adaptation measures seems to be justified only.

In contrast to that, this paper, which to our knowledge contributes the first rigorous analysis of the strategic aspects of funding adaptation, reveals controversial results. Within a two-stage non-cooperative game, where industrialized countries decide on funding adaptation in the first stage, and where all countries simultaneously choose their mitigation strategies in the second, it is shown: If strict complementarity between mitigation and adaptation exists in the sense that adaptation positively affects the marginal productivity of mitigation, then funding adaptation can improve the industrialized countries' welfare and stipulates global mitigation.[2] However, the welfare of the developing countries is negatively affected in this case. Developing countries will profit from funding adaptation only, if the impact of adaptation on the marginal productivity of mitigation is not positive, and thus, if the industrialized countries fund maladaptation or if adaptation is neutral to mitigation.[3] This indicates that the interaction between mitigation and adaptation is curcial in decision-making on funding adaptation.

The rest of this paper is organized as follows. Section 2 discusses some important interactions between mitigation and adaptation. The basic analytical framework is presented in Section 3. Section 4 analyzes under which conditions it is optimal for a country to accept funding adaptation, and whether there are incentives for industrialized countries to fund adaptation in developing ones. Section 5 then concludes.

2 On the interaction between mitigation and adaptation

Today there is broad consensus that due to past emissions the global climate is changing and that economies have to adapt (e.g. IPCC, 2007). Thus, climate policies, which aim for minimizing the social costs of climate change, have to consider both mitigation and adaptation. Analyses, which focus on mitigation solely and do not

[2] Klein et. al (2007) view *complementarity between mitigation and adaptation* as the interaction of these two measures, such that the outcome of one measure depends on the outcome of the other. We do not use this definition, but apply the one of Yohe and Strzepek (2007) instead, who define complementarity between mitigation and adaptation as the non-negative effect of one measure on the marginal productivity of the other.

[3] Maladaptation is an adaptation strategy which increases greenhouse gas emissions and hence, enhances the vulnerability of regions to climate change.

adequately account for adaptation, yield biased conclusions (see Toman, 1998). One must be aware, however, that the answer to the question how to combine adaptation and mitigation, very much depends on how adaptation and mitigation interact. For instance, the claim that an optimal climate policy should cover a mix of mitigation and adaptation strategies reflects the view that mitigation and adaptation are complementary tools for managing the risks of global climate change (e.g. Watson et al., 1996).

Unfortunately, the economic literature offers almost opposite views on the interaction between mitigation and adaptation. Parry et al. (2001) argue that mitigation and adaptation have to be undertaken simultaneously as they become more powerful in combating climate change when combined for at least two reasons: (1) Mitigation can buy time for adaptation through delaying impacts, i.e., more time is available for reducing a region's vulnerability through adaptation. (2) Adaptation can raise thresholds, which need to be avoided by mitigation. A typical example is increasing the drought tolerance of agricultural production through using more resistant crops. Yohe and Strzepek (2007) support the hypothesis that mitigation and adaptation can be viewed as complements, but in the sense that mitigation increases the productivity of adaptation.

The opposite view is taken by Tol (2005). He argues that mitigation and adaptation are substitutes, as they both can reduce climate impacts, but compete for scarce resources. Ingham et al. (2005) share his argument. Within a simple static model they show that mitigation and adaptation are substitutes in the sense that increasing the costs of mitigation will reduce the level of mitigation but increases that of adaptation and vice versa. This reflects the fact that adaptation and mitigation are almost equal options for reducing the social costs of climate change. Buob and Stephan (2007) observe a similar result. Based on the assumption that mitigation and adaptation are perfect substitutes with respect to their effects on environmental quality, they find that whether an optimal policy should combine mitigation and adaptation or not depends on the effect, global mitigation has on the marginal costs of adaptation.

The just mentioned papers have in common that they focus on the main characteristics of mitigation and adaptation only, and thus, analyze the interaction of mitigation and adaptation from a general perspective only. However, a review of the impact literature, which focuses on applied and detailed studies with respect to spatial and sectoral scale, again exhibits diverse views on the interrelationships between mitigation and adaptation. Case-based studies reveal that the implementation of adaptation strategies may affect the productivity of global mitigation and vice-versa as the following examples demonstrate.

The first one shows that mitigation can reduce the regions' vulnerability from which adaptation can profit. As Ravindranath (2007) discusses, land use, land-use change and forestry provide significant opportunities to sequestrate emissions of about two Gigatons of carbon annually. But blockading deforestation and forest degradation is not only an option for mitigating climate change. It also enhances adaptation by reducing the vulnerability of forest ecosystems because the multiple and native species of rich tropical forests are less vulnerable to climate impacts than monocultures or any artificial forests.

This is an example for complementarity between mitigation and adaptation in the sense that mitigation positively affects the marginal productivity of adaptation. Further examples are protected area management, afforestation and reforestation, where the latter are also included in Articles 3.3 and 12 of the Kyoto Protocol under CDM. Just the opposite effect on adaptation results from mitigation strategies such as substituting existing technologies through wind and waterpower or biofuels. This leads to a cutback of greenhouse gas emissions on the one hand, but negatively affects adaptation on the other, since these technologies increase the exposure, and hence, the vulnerability of regions to climate change (e.g. Dang et al., 2003). [4]

So far we considered examples, where mitigation affects adaptation. But adaptation might also affect mitigation. For instance, if adaptation includes changing hydrological regimes to enlarge water availability in water-scarce regions, additional energy inputs are required (see Boutkan and Stikker, 2004). The same holds true, if space heating or cooling is extended in order to protect citizens against temperature extremes. In both cases the expected effects on mitigation depend of the resulting changes in energy use, hence on the fossil fuel content of the technologies used for implementing these adaptation strategies (e.g. Klein et. al., 2007).

Note that adaptation, which increases emissions, is often called maladaptation. In contrast to maladaption, adaptation strategies exist, which positively affect mitigation.

[4] Other categories where mitigation strategies affect adaptation include: More efficient energy use and renewable sources that promote local development; CDM projects on land use or energy use that support local economies and livelihoods; health benefits of mitigation through reduced environmental stresses; effects of mitigation, e.g., through carbon taxes and energy prices, on resource use that affect adaptation, for example by reducing the use of tractors in semi-subsistence farming due to higher costs of fuels (Klein et al., 2007).

For instance, the conservation of water in urban areas reduces the energy use in moving and heating water (e.g. Klein et al., 2007).[5] Nevertheless, note that there are many adaptation strategies, which are neutral to mitigation and vice versa. Examples from the forest sector are: Mixed species forestry based afforestation, silvicultural practices such as thinning, sanitation harvest and fire protection (see Ravindranath, 2007).

3 A simple model of mitigation and adaptation

We consider a non-cooperative game, where the players are two regions. For vividness, they are called North and South. North (N) corresponds to the coalition of OECD countries, which have agreed to meet the Kyoto targets. South (S) is an acronym for the developing part of the world, which is free of any obligations to mitigate greenhouse gas emissions.

Integrated assessment of global climate change requires discriminating between market and non-market damages. Non-market damages are negative impacts of climate change such as species losses, which cannot be valued by market prices. Market damages are costs, which can, in principle, be expressed in terms of GDP losses. In the case of agriculture and forestry, for example, there are market prices by which we can measure the value of output losses.

Integrated Assessment models link market damages directly to gross output (for an explanation, see Manne et al., 1995, Nordhaus and Boyer, 2000). For an illustration, let Y_n be the potential (i.e. without climate impacts) gross output of region n. Since climate change negatively affects the productivity of inputs, economic losses due to climate change are the lower, the more emissions are abated. If we neglect the thermal inertia lag between changes in atmospheric greenhouse gas concentration and the resulting climate effects, then market damages can be viewed as a function of the stock of atmospheric carbon as well as the region's vulnerability. That means, the fraction $\Phi_n(Q-M,\Omega_n)Y_n$ of conventional income, which remains at the

[5] Other categories where adaptation affects mitigation are: Tourism use of energy and water, with outcomes for incomes and emissions; resources used in adaptation, such as in large-scale infrastructure, increase emissions; natural resources managed to sustain livelihoods, more efficient community use of water, land, forests and other natural resources, improving access and reducing emissions (Klein et. al., 2007).

regions' disposal as green GDP, is a decreasing function of: (1) the stock of atmospheric carbon Q-M, where Q denotes the business as usual (i.e., without mitigation) stock and where $M = m_N + m_S$ denotes the total of regional contributions m_n, n = N,S to greenhouse gas abatement; (2) the critical value Ω_n of greenhouse gas concentration, which is specific to region n, and at which climate damage may destroy the entire GDP.

According to the Third Assessment Report (see McCarthy, 2001) adaptation refers to investments into processes, practices, or structures to moderate or offset the potential damages of global climate change, as well as to reduce the vulnerability of communities, regions, or countries to climatic change and variability. In other words, the lower is the climate vulnerability of region n, the higher must be the critical value Ω_n. And since regional vulnerability can be reduced by adaptation, the most simple way to introduce adaptation as decision variable into Integrated Assessment analysis is to specify Ω_n as an increasing function of investments into adaptation a_n. That means, green GDP $\Phi_n(Q - M, \Omega_n(a_n))Y_n$ now is a function of the business as usual stock of greenhouse gas concentration Q, global mitigation M and regional adaptation a_n. This allows to simplify and to represent green GDP of region n by a concave function $F_n(M, a_n)$[6] with global mitigation M and regional stock of adaptation $a_n = a_n^n + a_n^i$ as inputs, where a_n^n denotes region n's investment into own adaptation and a_n^i is the fraction funded by region $i \neq n$.

Let each region n = N, S act as if it were represented by a self-interested and rational player, who maximizes regional welfare U_n, which has the usual properties and depends on own consumption c_n only. Regional green GDP can be consumed domestically and/or invested into mitigation and adaptation. The costs of mitigation and adaptation are characterized by strictly convex, twice differentiable functions $g_n(m_n)$ and $h_n(a_n)$, respectively.

Now, since it is assumed that the North is committed to reduce greenhouse gas emissions in the long-term, but also has the option to fund adaptation in the South for achieving the long-term goals of the UNFCCC, this immediately leads to the questions: (1) Can funding adaptation by the North provide an incentive to the South to enhance its mitigation efforts? (2) How does funding adaptation affect global mitiga-

[6] $\partial F_n / \partial M > 0$, $\partial F_n / \partial a_n > 0$, $\partial^2 F_n / \partial M^2 < 0$, and $\partial^2 F_n / \partial a_n^2 < 0$, respectively.

tion? To appropriately answer these questions we use a non-cooperative two-stage game, which has the following structure:

Stage 1: The North decides on funding a_S^N units of the South's adaptation infrastructure. This funding is unconditional in the sense that the South is not obliged to meet any mitigation targets.

Stage 2: All regions then simultaneously decide on mitigation under Nash conjectures.

In other words, the North may use funding investments as a strategic device in order to provide incentives for the South to increase mitigation in a post Kyoto world. The South and the North then decide on mitigation after the adaptation funding by the North is observed. Finally let us simplify the analysis by using

Assumption: a_n^n*, the investment of region n in its own adaptation infrastructure, is exogenously given.*

This reflects the assumption that in each region there is a need for investing independently a fixed amount into own adaptation measures as some climate change is inevitable in the near-term.

4 Analysis

Subgame-perfect equilibriums are obtained by backward induction. A Nash equilibrium of stage 2 is a vector $(\tilde{m}_N, \tilde{m}_S)$, which, conditional to the first-stage investment a_S^N into the South's adaptation capacities, solves

$$\text{Max}\,\{U_S(c_S) \mid c_S \le F_S(M, a_S) - g_S(m_S) - h_S(\hat{a}_S^S)\},$$

$$\text{Max}\,\{U_N(c_N) \mid c_N \le F_N(M, a_N) - g_N(m_N) - h_N(a_S^N) - h_N(\hat{a}_N^N)\},$$

where $\hat{a}_n^n, n = N, S,$ denotes the exogenously given investment into a region’s own adaptation infrastructure.

Since $g_n'' > 0$ and $\partial^2 F_n / \partial M^2 < 0$, the first order conditions

(4.1) $$\frac{\partial F_n(M,a_n)}{\partial M} - g'_n(m_n) \le 0\text{ , n = N, S,}$$

have unique interior solutions. These enable to define best response functions $\tilde{m}_n = \Psi_n(a_n, \tilde{m}_i)$, $i \neq n$, n = N, S, which allow analyzing, how the decision to fund adaptation in the first stage of the game affects equilibrium mitigation in the second stage.[7]

From condition (4.1) follows

(4.2) $$\frac{\partial \Psi_n}{\partial \tilde{m}_i} = -\left(\frac{\partial^2 F_n / \partial \tilde{M}^2}{\partial^2 F_n / \partial \tilde{M}^2 - g''_n(\tilde{m}_n)} \right) \in (-1,0)^8,$$

which indicates that region n will reduce its greenhouse gas abatement, but by less than unity, if its rival increases greenhouse gas mitigation by one unit. Hence, despite the reduction in region n's mitigation level, induced by an increase in region i's mitigation efforts, global mitigation is increased.

In contrast to that, the interaction between mitigation and adaptation depends on how adaptation affects the marginal productivity of mitigation. Since

$$\frac{\partial \Psi_n}{\partial a_n} = -\left(\frac{\partial^2 F_n / \partial \tilde{M} \partial a_n}{\partial^2 F_n / \partial \tilde{M}^2 - g''_n(\tilde{m}_n)} \right),$$

we have

[7] Note that our model does not allow us to examine under which conditions adaptation funding provides an incentive to developing countries to engage from zero to a positive level of mitigation. Our focus lies on the effects of funding adaptation on mitigation undertaken by the South and the North given positive levels of mitigation.

[8] Note, condition (4.2) only holds, if $\left| \frac{\partial^2 F}{\partial M^2} \right| > g''(\tilde{m}_n)$. This is fulfilled for $\tilde{m}_n > 0$ producing a net gain.

(4.3) $$\frac{\partial \Psi_n}{\partial a_n}\begin{cases} >0, \text{ if } \partial^2 F_n / \partial \tilde{M} \partial a_n > 0 \\ =0, \text{if } \partial^2 F_n / \partial \tilde{M} \partial a_n = 0 \\ <0, \text{ if } \partial^2 F_n / \partial \tilde{M} \partial a_n < 0 \end{cases}.$$

Therefore, if mitigation and adaptation are complementary inputs into green GDP, i.e., if $\partial^2 F_n / \partial M \partial a_n \geq 0$, an increase of region n's stock of adaptation does not reduce region's mitigation.[9] But if adaptation negatively affects the marginal productivity of mitigation, i.e., $\partial^2 F_n / \partial M \partial a_n < 0$, then an increase in the adaptation level of region n leads to a reduction in the mitigation level of region n.

4.1 Interaction between adaptation funding and global mitigation

As the second-stage equilibrium is unique, equilibrium mitigation must satisfy $\tilde{m}_n = \Psi_n(a_n, \Psi_i(a_i, \tilde{m}_n))$, i ≠ n, n = N,S. Since $da_N = 0$, $da_S = da_S^N > 0$, differentiating and rearranging yields

(4.4) $$\frac{d\tilde{m}_N}{da_S^N} = \left[\frac{\partial \Psi_N}{\partial \tilde{m}_S}\frac{\partial \Psi_S}{\partial a_S}\right]\left(1 - \frac{\partial \Psi_N}{\partial \tilde{m}_S}\frac{\partial \Psi_S}{\partial \tilde{m}_N}\right)^{-1},$$

(4.5) $$\frac{d\tilde{m}_S}{da_S^N} = \left[\frac{\partial \Psi_S}{\partial a_S}\right]\left(1 - \frac{\partial \Psi_N}{\partial \tilde{m}_S}\frac{\partial \Psi_S}{\partial \tilde{m}_N}\right)^{-1}.$$

By using these conditions we observe

(4.6) $$\frac{d\tilde{M}}{da_S^N} = \frac{\partial \Psi_S}{\partial a_S}\left(1 + \frac{\partial \Psi_N}{\partial \tilde{m}_S}\right)\left(1 - \frac{\partial \Psi_N}{\partial \tilde{m}_S}\frac{\partial \Psi_S}{\partial \tilde{m}_N}\right)^{-1}.$$

[9] Remember that in case of a production function which exhibits increasing marginal productivity in all inputs, then there is complementarity between the inputs, if the cross derivatives are greater or equal to zero (see Mas-Colell et. al., 1995).

This and conditions (4.2) and (4.3) then prove

Proposition 1: Suppose, adaptation is marginally increased in the South, then

$$\frac{d\tilde{M}}{da_S^N} = 0, \ \textit{if} \ \frac{\partial^2 F_S}{\partial \tilde{M} \partial a_S} = 0,$$

$$\frac{d\tilde{M}}{da_S^N} > 0, \ \textit{if} \ \frac{\partial^2 F_S}{\partial \tilde{M} \partial a_S} > 0,$$

$$\frac{d\tilde{M}}{da_S^N} < 0, \ \textit{if} \ \frac{\partial^2 F_S}{\partial \tilde{M} \partial a_S} < 0.$$

Proposition 1 states that investing into the South's adaptation infrastructure does not decrease global mitigation, if adaptation and mitigation are complementary inputs. For, if adaptation increases the marginal productivity of mitigation, then the South is willing to take a higher burden of greenhouse gas mitigation. In response (see condition (4.2)), the North reduces mitigation by less than unity, and global mitigation rises nonetheless. Conversely, global mitigation decreases, if mitigation and adaptation are non-complementary inputs.

Let us exemplify this result. Suppose, the North invests into water conservation projects in the South to reduce the South’s vulnerability regarding potential water scarcity. Such an investment positively affects mitigation, since it reduces the energy use for transporting, heating and cooling of water. The South then reacts by investing into mitigation to further reduce the energy use as a response to the increased marginal productivity of mitigation caused by the adaptation funding. In turn, the North reduces its mitigation level due to the South’s willingness to increase its mitigation efforts. Nevertheless, global mitigation increases, because the North reduces its mitigation level by less than the mitigation increase by the South.

The opposite holds for adaptation measures funded by the North which negatively affect the marginal productivity of mitigation. Examples are investments into infrastructures, which aim at recycling wastewater and which in turn negatively affect the productivity of mitigation due to the increased energy use in the recycling process. Hence, if the North funds maladaptation global mitigation decreases. However note that funded adaptation, which is neutral to mitigation, leaves the global mitigation level unaffected.

4.2 Welfare effects

From an ecologist's perspective, increasing greenhouse gas abatement has its own value, but from an economist's point of view the welfare effects matter. Therefore, let us consider the effect of funding adaptation on regional welfare. Given the assumption that both regions engage in mitigation, how does a marginal, but unilateral investment into the South's adaptation infrastructure affect the welfare of both regions? Based on welfare optimization we get

$$\frac{dU_S}{da_S^N} = U_S'\left(\frac{\partial F_S}{\partial a_S} + \frac{\partial F_S}{\partial M}\frac{dM}{da_S^N} - g_S'\frac{dm_S}{da_S^N}\right).$$

Since condition (4.1) must be satisfied, conditions (4.5) and (4.6) imply

$$\text{(4.7)} \qquad \frac{dU_S}{da_S^N} = U_S'\left[\frac{\partial F_S}{\partial a_S} + \frac{\partial F_S}{\partial M}\frac{\partial \Psi_S}{\partial a_S}\frac{\partial \Psi_N}{\partial m_S}\left(1 - \frac{\partial \Psi_N}{\partial m_S}\frac{\partial \Psi_S}{\partial m_N}\right)^{-1}\right],$$

which, because of conditions (4.2), (4.3), and $\frac{\partial F_S}{\partial a_S} > 0$ proves:

Proposition 2: Suppose, adaptation is marginally increased in the South, then $dU_S / da_S^N > 0$*, if* $\partial^2 F_S / \partial M \partial a_S \leq 0$*.*

Now, if there is no strict complementarity between adaptation and mitigation, i.e., $\partial^2 F_S / \partial M \partial a_S \leq 0$, then funding adaptation in the South reduces mitigation in that region. The North reacts by extending his mitigation efforts, as condition (4.2) indicates. Consequently, the South will benefit: It can reduce the burden of greenhouse gas mitigation on one hand, while its potential GDP losses are compensated through adaptation on the other.

Let us explain this again at hand of an example. If the North funds investments into space cooling equipment in order to protect citizens from increased temperatures due to climate change the South will profit, since citizens are now less vulnerable to the heat. But these adaptation investments will increase emissions due to the increase in energy use for running the cooling equipments. Since these adaptation investments negatively affect the marginal productivity of mitigation, the South substitutes away from mitigation to consumption. The North anticipates the South's reaction and responds with an increase in its mitigation efforts in order to minimize climate damages. Nevertheless, the welfare of the South is increased, because benefits from higher adaptation and consumption levels exceed the losses due to the lower level of global mitigation. In other words: the South's welfare is increased, if the North funds maladaptation.

Note that the South's welfare is also increased by a marginal increase of the South's adaptation stock if adaptation is neutral to mitigation, i.e., $\partial^2 F_S / \partial M \partial a_S = 0$. Since there is no effect of the funded adaptation measure on the marginal productivity of mitigation, the South does not respond to the increased funding through changes in its mitigation level (see condition (4.3)). In this case, the South profits from reduced damages caused by a higher level of adaptation and thus, from a higher level of green GDP which is used for consumption purposes.

So far, our analysis reveals an unpleasant result. On the one hand, overall mitigation increases, if adaptation and mitigation are strict complementary inputs in green GDP. On the other hand, investing in the South's adaptation infrastructures positively affects the welfare of that region only, if the funded adaptation measures non-positively affect the marginal productivity of mitigation in the South. This is of particular importance, if we want to consider under which conditions the North is willing to invest into adaptation infrastructures in the South. Therefore, let us discuss: What are the effects of funding adaptation in the South on the welfare of the North?

For answering this, let us consider the North's first stage decision problem. Let $\tilde{m}_N$ and $\tilde{M}$ denote equilibrium mitigation of the second stage, then the optimal funding is determined by

$$\max \{U_N(F_N(\tilde{M}, \hat{a}_N,) - g_N(\tilde{m}_N) - h_N(a_S^N) - h_N(\hat{a}_N^N)\}.$$

Totally differentiation gives

$$\frac{dU_N}{da_S^N} = U_N'(\frac{\partial F_N}{\partial \tilde{M}}\frac{d\tilde{M}}{da_S^N} - g_N'\frac{d\tilde{m}_N}{da_S^N} - h_N'(a_S^N)).$$

This implies that the decision to invest into adaptation in the South depends on the indirect effects, i.e., effects of changes in the South's adaptation infrastructure on mitigation $\tilde{m}_S$. And since $h_N' > 0$, the North will support adaptation in the South only, if

$$(\frac{\partial F_N}{\partial \tilde{M}}\frac{d\tilde{M}}{da_S^N} - g_N'\frac{d\tilde{m}_N}{da_S^N}) = (\frac{\partial F_N}{\partial \tilde{M}} - g_N')\frac{d\tilde{m}_N}{da_S^N} + \frac{\partial F_N}{\partial \tilde{M}}\frac{d\tilde{m}_S}{da_S^N} > 0.$$

However, since condition (3.1) has to be satisfied in equilibrium for $\tilde{m}_N > 0$, adaptation and mitigation must be strict complementary inputs as immediately follows from condition (3.3) and (3.5).

Proposition 3: The North funds adaptation in the South only, if $dU_N / da_S^N \geq 0$*, and thus, if* $\partial^2 F_S / \partial M \partial a_S > 0$.

Overall, our analysis reveals a controversial result. On the one hand, the North is willing to invest into the South's adaptation measures only, if $\partial^2 F_n / \partial M \partial a_n > 0$, hence, if there is strict complementarity. That is, the North funds adaptation in the South only, if these adaptation measures make mitigation more productive. An example is the planting of trees in urban areas, which not only protects citizens from the heat but also affects mitigation via the carbon uptake of the trees. On the other hand, funding adaptation in the South positively affects that region's welfare only, if adaptation measures are neutral to mitigation or if no complementarity between mitigation and adaptation exists, i.e., if the North invests into maladaptation (see Proposition 2).

5 Concluding thoughts

Within the framework of non-cooperative two-stage game, where in the first stage the North decides on funding adaptation in the South, and where both regions simultaneously decide on mitigation in the second, this paper gives answers to the questions: Does the North have an incentive to invest into the South's adaptation infrastructure? Does funding adaptation positively affect the South's willingness to reduce greenhouse gas emissions? How does funding adaptation affect global mitigation?

Overall our analysis reveals a controversial result. On the one hand it is shown that the North has an incentive to fund adaptation in the South only, if adaptation has a positive effect on the marginal productivity of mitigation in the South, and hence, if funding adaptation stipulates the South to increase its mitigation efforts. This reinforces the claim of the Intergovernmental Panel of Climate Change that synergies between mitigation and adaptation can increase the attractiveness of funding adaptation by funding agencies (see Parry, 2007). Unfortunately, however, the South's welfare is negatively affected in this case. On the other hand, the South's welfare is increased through funding, if adaptation and mitigation are neutral or if adaptation reduces the marginal productivity of mitigation. This means that the South is better off only, if the North funds maladaptation or if adaptation measures are funded, which do not affect the productivity of mitigation.

The results indicate how the present analysis differs from the existing literature. We are not analyzing whether mitigation and adaptation are complements or substitutes in the economic sense. Our analysis rather makes aware of the necessity to consider the interrelationship between mitigation and adaptation, if climate policies should be designed, which include adaptation funding. Therefore, not only our understanding of the cross-linkages between mitigation and adaptation has to be improved for providing more risk reduction at lower costs as is required by Kane and Shogren (2001). It is necessary also to carefully decide on what kind of adaptation measures should be funded.

Besides that, there is a further politically relevant message. As long as the levels of contributions to greenhouse gas mitigation are not fixed and thus, voluntary, funding the developing countries' adaptation might be inefficient. Consequently, funding adaptation should be incorporated into an international agreement, where both the industrialized and developing countries contribute to greenhouse gas abatement. In a cooperative world, the positive externalities, which greenhouse gas abatement by one region has on the welfare of the other, are completely internalized. Thus, in a social optimum mitigation as well as the funded adaptation are higher than in a world, where countries act non-cooperatively. Furthermore, the optimal adaptation funding is independent of whether mitigation and adaptation are complementary or non-complementary inputs (see Appendix for more details) .The results of the cooperative game then allow defining the interrelationship between mitigation and the funded adaptation in an international agreement. However, we leave the analysis of such an international agreement on the optimal funding of adaptation and mitigation to future research.

Obviously, there are further options for extending the present analysis. One could be to account for the differences in the time horizons, on which mitigation and adaptation become effective, since due to the inertia of the climate system the benefits of mitigation accrue in the long-term, whereas the benefits of adaptation are likely to be experienced in the short-term. This would mean making the model a dynamic one. An extension of the analysis could be to allow for uncertainty. For example, benefits of greenhouse gas mitigation could be viewed as uncertain, because it might take decades until mitigation will become effective. Conversely, the benefits of adaptation can be viewed less uncertain, since the benefits of adaptation may occur within a much shorter time.

6 References

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Appendix

Let $\dot{m}_n$, n = N,S, and $\dot{a}_S^N$ denote the Pareto-efficient levels of mitigation and funded adaptation, respectively, which result from maximizing the welfare function

$$\alpha_N U_N(c_N) + \alpha_S U_S(c_S),$$

where α_n, n = N,S, defines a region specific weight, subject to the budget constraints

$$c_S \le F_S(M, a_S) - g_S(m_S),\ c_N \le F_N(M, a_N) - g_N(m_N) - h_N(a_S^N).$$

First order conditions entail in case of interior solutions

(5.1) $$\alpha_N U_N' \frac{\partial F_N}{\partial \dot{M}} + \alpha_S U_S' \frac{\partial F_S}{\partial \dot{M}} - \alpha_n U_n' g_n'(\dot{m}_n) = 0,\ n = N, S,$$

(5.2) $$\alpha_S U_S' \frac{\partial F_S}{\partial \dot{a}_S} = \alpha_N U_N' h_N'(\dot{a}_S^N).$$

Condition (5.1) implies that in a cooperative world the positive externalities mitigation by one region imposes on the other are internalized. Therefore, both regional and global mitigation is higher than in a non-cooperative equilibrium (see condition (4.1)). Furthermore note that the socially optimal mitigation level of the North is an increasing function of α_S. In other words, the higher the value placed on the well-being of the South the more greenhouse gases must be mitigated to achieve the first-best optimum.

Condition (5.2) shows that it is Pareto-optimal to fund adaptation, if the marginal benefits of the South equal to the marginal costs the North has to bear. This is in contrast to what was observed in the non-cooperative game, where the decision to support adaptation depends on indirect effects and thus, on whether there is complementarity between mitigation and adaptation. Again, the higher the weight placed on the welfare of the South, the higher optimal investments into adaptation funding need to be to achieve the social optimum.

Now, combining (5.1) and (5.2) yields

$$g'_N(\dot{m}_N)\frac{\partial F_S}{\partial \dot{a}_S} - g'_S(\dot{m}_S)h'_N(\dot{a}_S^N) = 0 .$$

This defines the relationship between optimal funding of adaptation $\dot{a}_S^N$ and optimal mitigation $\dot{m}_n$, n= N,S, which need to hold in an international agreement where funding adaptation depends on regional efforts for curbing greenhouse gas emissions.