To Mitigate or To Adapt? Strategies for Combating with Climate Change

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PRELIMINARY AND INCOMPLETE. COMMENTS ARE WELCOME.

Abstract

Adaptation and mitigation are the most important policy options in responding to the threat of global climate change. But even if adaptation and mitigation were equally effective in protecting against potential damages from global warming, there are significant differences between these two measures. Adaptation may generate private benefits which are local and likely to be experienced over the short term, whereas the benefits of mitigation are public, global and experienced over the long term. This paper analyzes adaptation and mitigation as well as their interaction within the framework of non-cooperative game between identical countries. Central to the analysis is the assumption that whatever effects a country can achieve, for its own sake, through mitigation can also be achieved through adaptation, and vice versa. Based on that we observe two polar results: (1) If all countries choose simultaneously the optimal levels both of adaptation and mitigation, there is a continuum of equilibria, where the equilibrium with zero adaptation is Pareto optimal. (2) In a dynamic setting where mitigation is chosen first and adaptation second and where the benefits of mitigation accrue only in the future, there is a unique equilibrium with zero mitigation. Assuming then that future marginal costs of adaptation negatively depend on the present environmental quality and on the mitigation effort by all countries, we observe that in equilibrium countries undertake mitigation as well as adaptation.

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1 Introduction

Mitigation of greenhouse gases is one of the cornerstones of global climate policy. By the United Nations Framework Convention on Climate (UNFCCC), the so called Kyoto Protocol, the majority of the industrialized countries has agreed to reduce collectively their carbon dioxide emissions by 5,2 percent (compared to 1990 levels) over the period 2008 - 2012. However, abating greenhouse gas emissions through mitigation is not the only option in responding to the threat of global climate change. Alternatively, there exists the possibility to reduce a region's vulnerability by adapting to the undesired impacts of global warming. Thereby, adaptation can cover a wide range of different measures, including early warning on the one end and investments into protecting infrastructures such as dams for preventing against flooding on the other.[1]

Today, it has become more and more apparent that the Kyoto Protocol will be relatively ineffective in insuring against the risks of global climate change. One reason is that the emission reduction targets set in the Protocol are too low. But even more radical reduction targets would not imply a significant slow down of the rate of global warming as long as these targets are binding for the Annex I countries only and as long as the fast growing regions of Asia, India or Latin America are exempted from the duty of reducing their domestic carbon dioxide emissions. Consequently, greenhouse gas mitigation cannot be the sole policy response to global climate change. Given the inertia of the climate system it is to be expected that adaptation will have, at least in the near term, greater effects in preventing against disastrous impacts from climatic variability than does mitigation.

Nevertheless, adaptation has not received much attention, neither by policy makers nor by scientists. One reason might be that political correctness has prevented a discussion of adaptation to climate change "because it presumably implies defeat in the battle against evil emissions." (see Tol (2005)). A second and closely related reason could be that the majority of the developing countries cannot effort significant adaptation measures, whereas industrialized nations might use adaptation as a substitute for greenhouse gas mitigation, and hence might reduce their engagement in carbon dioxide abatement (see Berkhout (2005)).

Conventional economic wisdom supports this argument. Adaptation is significantly different from mitigation. It generates benefits which are private to the

[1] According to the Intergovernmental Panel of Climate Change (IPCC) mitigation is defined as intervention to reduce anthropogenic greenhouse gases emissions or to enhance sinks. Adaptation refers to investment 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 for details, see Intergovernmental Panel of Climate Change, Working Group 2 (2001), Intergovernmental Panel of Climate Change, Working Group 3 (2001).

regional societies, whereas benefits from mitigation are public. And benefits from adaptation are likely to be experienced over the short term, whereas benefits from greenhouse gas mitigation will be experienced over the long term. Consequently, economic rationality suggests to prefer adaptation over mitigation, whenever this is feasible. And there is a further argument in favor of adaptation. While adaptation can be provided by each country independently, sufficient benefits from greenhouse gas mitigation will be realized only through collective actions. That means in particular, without some binding international arrangement for abatement and burden-sharing greenhouse gas mitigation will be more or less ineffective cosmetics (see Heal (1990)).

Although the interplay between adaptation and mitigation should be of some interest, not only to environmentalists but also to economists, there are only a few papers which explicitly consider adaptation and mitigation as parts of a policy response to the problem of global climate change. Examples are, among a few others, Kane and Shogren (2000), Klein, Schipper, and Dessai (2003), McKibbin and Wilcoxen (2003), or McKitrick (2001).[2] These papers have in common that they elaborate on what features are important in designing a climate policy to encourage both, low cost mitigation and adaptation strategies.

Here we will return to the more fundamental issue, which was motivated above. Suppose that adaptation and mitigation can be substitutes in protecting a region from impacts of global climate change. And suppose that there exists no international enforceable contract for abatement and burden sharing, i.e. each country can choose what is best for its own. Wouldn't it be rational then from the perspective of a single country to invest into adaptation primarily instead of engaging in greenhouse gas mitigation?

Our analysis, which is based on a simple model of a non-cooperative game[3], where regions are players and where the strategies at hand are mitigation and adaptation, makes a first step towards answering this question. It is shown that if all countries simultaneously choose their optimal levels of both adaptation and mitigation, there is a continuum of equilibrium solutions. These can be Pareto ranked, and the equilibrium with zero adaptation is best. However, if we allow

[2]It should be noted that integrated assessment models such as MERGE (see Manne, Mendelsohn, and Richels (1995)), or RICE (see Nordhaus and Yang (1996)) implicitly capture adaptation by integrating the costs of adaptation into the regional damage function.

[3]To our knowledge this is the first paper that addresses the joint effects of mitigation and adaptation in a game theoretic framework. Tol (2005) discusses adaptation and mitigation, yet does not perform a game theoretic analysis. Dutta and Radner (2004), Dutta and Radner (2006a) and Dutta and Radner (2006b) analyze climate change policies in a game theoretic framework, but their approach differs from ours in two important ways. First, they study Pareto optimal and non-cooperative agreements in an infinite dynamic game, whereas we study static or two-period games. Second, they focus entirely on mitigation.

for step by step decision with mitigation is chosen first and adaptation is chosen second, then there is a unique equilibrium with zero mitigation.

Obviously, to assume that mitigation and adaptation are perfect substitutes exaggerates reality. There is evidence that some of the benefits, a country can achieve through mitigation, can also be achieved through adaptation, and vice versa. However, this is feasible to a limited extend only. Nevertheless let us stick to this, perhaps unrealistic assumption to make unmistakable clear: In a world without cooperation in the solution of the global climate problem, adaptation is by no means the optimal policy response as might be expected. Mitigation can be Pareto superior, because mitigation provides externalities from which all countries can profit and thus, undertaking mitigation is socially preferable. But this relates to a situation only, where the temporal dimension is neglected. If time and sequential decision making is taken into account, just the opposite is observed: There is a unique equilibrium with zero mitigation. The reason is that discounting now matters (see Kane and Shogren (2000)). The higher the discount rate, the lower is the present value placed on future benefits, and since payoffs of mitigation will typically be realized later than those of adaptation, adaptation creates higher net-benefits, if the discount rate is greater than zero.

Since mitigating emissions improves future environmental quality, which in turn affects the future costs of adaptation, e.g. smaller and/or less dams need to be built if the degree of sea level rise is low, we therefore extend our dynamic framework by introducing different marginal costs of mitigation and adaptation. It is assumed that the higher the initial environmental quality and the more mitigation effort is undertaken by all countries, the smaller are the marginal costs of adaptation in the future. Solving for the equilibrium in this extended dynamic setting yields an equilibrium outcome, where both mitigation and adaptation are undertaken. However, for a high present environmental quality, countries undertake more adaptation and less mitigation compared to a condition, where the present environmental quality is low. This result is driven by the assumption that the higher the environmental quality the lower the costs for adaptation. We furthermore show that the larger the life-time endowment of a country is, the larger is the range of potential initial environmental qualities, for which countries invest into both, mitigation and adaptation. In other words, the larger a country's life-time endowment is, the larger is it's scope to invest into mitigation and adaptation.

The rest of this paper is organized as follows. Section 2 presents our basic modeling framework. Section 3 derives the equilibrium solution of the static game, where all countries choose their mitigation and adaptation efforts simultaneously. Section 4 solves for the equilibrium in the dynamic game, where mitigation is chosen first and adaptation second, respectively. In section 5 the dynamic game is extended by introducing a different cost structure, where the costs of adaptation depend on the initial environmental quality and the mitigation effort undertaken by all countries. Finally, Section 6 covers some concluding remarks. Note that proofs are delegated to the Appendix.

2 The Basic Framework

For analyzing the interplay between mitigation and adaptation let us consider a non-cooperative player game which is simple enough to be transparent and sufficiently complex to capture the essential aspects of reality. Suppose, the world economy is divided into n regions. These could be either single countries such as the U.S. or supranational entities like the EU. Each region i, $i = 1, .., n$, acts as if it were represented by a self-interested and rational player who maximizes regional welfare $U_i(c_i, e_i)$, which depends on the consumption of a private good c_i as well as on environmental quality e_i. As usual, there are positive but diminishing marginal rates of welfare.

The level of environmental quality e_i, which is available to region i, is determined by (1) the initial environmental quality E, which is exogenously given and identical for all regions, (2) the adaptation activity $a_i \in [0, \infty)$, which is carried out in region i, and (3), by the total $M \equiv \sum_{j=1}^{n} m_j$ of all regional contributions $m_j \in [0, \infty)$, $j = 1, ..., n$ to greenhouse gas mitigation. Formally, this relationship is expressed by

$$e_i = F_i(E, M, a_i).$$

Note that F_i might be viewed as a production function, where the output e_i is private to region i, and where the inputs are public (mitigation) and/or private (adaptation), respectively.

For simplicity, let for each region i the endowment of conventional wealth y_i be exogenously given. Regional income can be spent on private consumption and/or adaptation as well as greenhouse gas mitigation. Consequently, since adaptation and mitigation are the decision variables at hand, the consumption of the private good c_i is given by the constraint

$$c_i = y_i - a_i - m_i. \tag{1}$$

Let us reduce the burden of analytic calculations by using a Cobb-Douglas formulation of the utility function throughout this paper, i.e.

$$U_i = \alpha \ln(c_i) + (1 - \alpha) \ln(e_i), \tag{2}$$

where $\alpha \in (0,1)$ is the elasticity of consumption. Furthermore, let us restrict attention to the symmetric case where $y_i = y$ for all i.

We do not believe that our results are very much driven by these specific assumptions. Of course, relaxing clearly seems desirable, but this is left for future work. The following assumption, however, is crucial as was already pointed out in the introduction.

Assumption 1 *For each country i let*

$$e_i = E + M + a_i. \tag{3}$$

Obviously, this implies that adaptation and mitigation are perfect substitutes. Remember, however, that despite of being equally effective in protecting a region against potential damages from global climate change, there still is an important difference between adaptation and mitigation: Adaptation is private to the specific region, whereas mitigation creates positive external effects on all other.

3 The Static Game

Let us start the analysis by assuming that all countries i simultaneously fix their optimal levels of both adaptation a_i and mitigation m_i. For short this will be called a static game in contrast to the dynamic game with sequential decision making and complete information, which is considered in Section 4.

By substituting e_i through equation (3) and c_i by the regional budget constraint (see equation (1)), the regional payoffs (see equation (2)) can directly be expressed in terms of adaptation and mitigation strategies

$$\alpha \ln(y - a_i - m_i) + (1-\alpha)\ln(M + a_i).^4 \tag{4}$$

This immediately implies the following first order conditions, which have to be satisfied in equilibrium for any i, $i = 1, ..., n$

$$-\frac{\alpha}{y - m_i - a_i} + \frac{1-\alpha}{M + a_i} = 0 \tag{5}$$

$$-\frac{\alpha}{y - m_i - a_i} + \frac{1-\alpha}{M + a_i} = 0. \tag{6}$$

Both conditions are identical, which is due to the assumption that adaptation and mitigation are perfect substitutes. Consequently, there are n equations in $2n$ unknowns, which read for any $i = 1, ..., n$ after rewriting either condition (5) or condition (6),

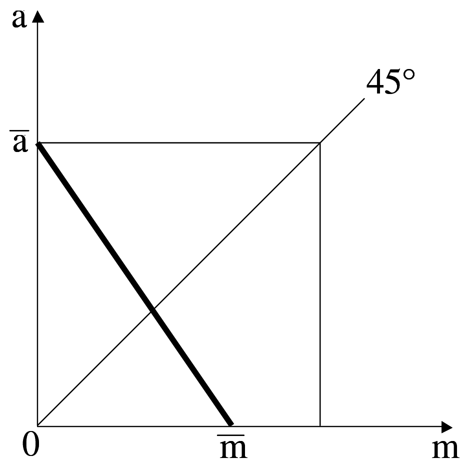

Figure 1: Continuum of Symmetric Equilibria.

$$m_i + a_i = (1-\alpha)y - \alpha M_{-i}, \tag{7}$$

where $M_{-i} \equiv \sum_{j \neq i} m_j$. Not surprisingly then, our first result will be that there are multiple equilibria. For being precise, let us introduce some useful definitions. Let

$$\overline{a} \equiv (1-\alpha)y \quad \text{and} \quad \overline{m} \equiv y\frac{1-\alpha}{1-\alpha+\alpha n},$$

which in particular implies $\overline{a} > \overline{m}$ if $n > 1$, and let an equilibrium be called symmetric if all players i choose the same actions (a_i, m_i).

Proposition 1 *In the static game, there is a continuum of symmetric equilibria (a^*, m^*) with $a^* \in [0, \overline{a}]$, $m^* \in [0, \overline{m}]$ and*

$$a^* = \overline{a} - (1-\alpha+\alpha n)m^*. \tag{8}$$

As Figure 1 indicates, the set of all pairs (a^*, m^*) of adaptation and mitigation strategies, a country can play in a symmetric equilibrium, forms a straight line which has a slope steeper than 1 for $n > 1$. And since the technological rate of substitution between adaptation and mitigation is one, this implies that there must be differences in regional welfare across the different equilibria. Intuitively, this can be explained as follows. Suppose, country i intends to substitute mitigation by adaptation. In a symmetric equilibrium all countries will act in the same way. Now, since adaptation is private but mitigation is public, in order to keep the level of regional environmental quality, country i has to replace through adaptation (1) its own short-cut of mitigation plus (2), the short-cut in mitigation effort of all other countries. Therefore, the fraction of regional income that country i additionally has to spend on adaptation is larger than its original contribution to greenhouse gas mitigation. More precisely, we can formulate the following Proposition.

Proposition 2 *The set of symmetric equilibria can be Pareto ranked: The less adaptation and the more mitigation is undertaken in an equilibrium, the higher the equilibrium welfare for every country.*

Proposition 2 in particular implies that there exists a uniquely determined Pareto efficient equilibrium. This is the one on the bottom right in Figure 1, i.e., where $a_i^* = 0$ and $m_i^* = \overline{m}$ for all i. Incidentally, the same equilibrium would be obtained in a game without adaptation. As such proposition 2 provides a strong argument against adaptation as a policy tool in combating with global climate change. Adaptation might only add Pareto inferior equilibria, because of the fact that in addition to regional protection mitigation can produce a positive externality from which all can profit.

Note that though our focus on symmetric equilibria, there are also asymmetric equilibria, which widely vary with respect of distributional effects (details can be found in Appendix B). For example, in the case of two players only, $(a_1^* = 0, m_1^* = \overline{a})$ and $(a_2^* = (1-\alpha)\overline{a}, m_2^* = 0)$ defines an equilibrium, in which country 1 fares much worse than country 2 as the latter free rides to considerable degree on country 1's mitigation efforts. Furthermore, it can be shown that country 2, who free rides on country 1's mitigation efforts, and who invests into adaptation only, is better off in equilibrium than in the symmetric case where both countries undertake mitigation actions in equilibrium, i.e. $U_2^{ASYM}(a_2^*) > U_2^{SYM}(\overline{m})$. This is an interesting result, since it supports the argument mentioned above, that industrialized countries would prefer not to invest into emission reduction measures but to adapt to climate change.

Let us now return to the symmetric case again. Proposition 2 motivates two questions. First, if adaptation leads to Pareto inferior outcomes, why should adaptation ever be perceived and portrayed as a valuable policy option? Second, since the equilibrium with mitigation only is Pareto efficient, doesn't this suggest that cooperation counts? For answering this question, let us discuss how the Pareto-efficient equilibrium relates to levels of mitigation and adaptation which are socially optimal.

Socially optimal levels of mitigation and adaptation are solutions of the problem

$$\max_{a_1,\dots,a_n,m_1,\dots,m_n} \quad \sum_{j=1}^{n}[\alpha \ln(y_j - a_j - m_j) + (1-\alpha)\ln(M + a_j)]. \tag{9}$$

Recall that in contrast to the equilibrium solutions of the static game as obtained above, a social optimum requires cooperation, just as friends do, when they share both costs and fun of a meal. This has an important consequence. While adaptation and mitigation are perfect substitutes from an individual perspective, adaptation is clearly less desirable than mitigation from a social perspective: Anything a country can achieve via adaptation can also, and with exactly the same cost, be achieved through mitigation. But mitigation has the additional advantage that all the other countries can benefit. Clearly then, for achieving a social optimum any region i must set $a_i = 0$.

Maximizing (9) with respect to m_i while keeping $a_i = 0$ for all i gives the first order conditions

$$-\frac{\alpha}{y - m_i} + \frac{1-\alpha}{M} + \sum_{j \neq i} \frac{1-\alpha}{M} = 0, \tag{10}$$

or because of symmetry

$$\frac{\alpha}{y - m} + \frac{n(1-\alpha)}{M} = 0 \tag{11}$$

and finally because of $M \equiv nm$

$$m = (1-\alpha)y \equiv \overline{a}. \tag{12}$$

Not surprisingly then, the socially optimal amount of mitigation exceeds the equilibrium level of mitigation $\overline{m}$ in the Pareto optimal equilibrium, since $\overline{a} > \overline{m}$ for $n > 1$.

4 The Dynamic Game with Full Information

As was mentioned earlier, there is a significant difference between adaptation and mitigation, even if they are perfect substitutes in their effects on the regions' environmental quality: Benefits of mitigation will typically will be realized in the somewhat far distant future whereas the society can profit almost instantaneously from adaptation.[5] This motivates to extend the analysis of the interaction between mitigation and adaptation into a dynamic setting by considering the following non-cooperative 2-stage game.

- Stage 1: All regions simultaneously choose their mitigation strategies. These choices then become public.
- Stage 2: All regions simultaneously choose their adaptation measures under Nash conjectures.

[5] Though, in reality, it also takes some time, before adaptation exhibits a positive impact, it is arguably much more flexible and amenable than mitigation efforts.

Typically, such a game is solved by applying backwards induction. To that end, let the time horizon cover just two periods $t = 1, 2$. y_i now denotes the life-time endowment of conventional wealth which is exogenously given to region i at the beginning of the time horizon, and let m_i denote the mitigation level, which players simultaneously choose at the beginning of period 1 together with their first-period consumption $c_{1,i}$, and their savings s_i, which determine the income that is at a region's disposal in the second period.

After having observed the world's total mitigation efforts M, at the beginning of period 2 players simultaneously determine their optimal levels of adaptation a_i as well as their second-period consumption $c_{2,i}$ by maximizing the second stage objective function

$$U_{2,i} = \alpha \ln(c_{2,i}) + (1-\alpha)\ln(E + M + a_i) \tag{13}$$

subject to the second period budget constraints

$$s_i = c_{2,i} + a_i. \tag{14}$$

E denotes the initial environmental quality which is exogenously given to the regions at the beginning of the time horizon. Note, however, that regions can improve the future environmental quality through climate policy inventions such as adaptation and mitigation.

Solving this optimization problem yields the optimal levels for adaptation and consumption for a region i, which, because of symmetry between regions, read as follows

$$\widehat{a} = (1-\alpha)s - \alpha(M + E) \tag{15}$$

$$\widehat{c_2} = \alpha(s + M + E) \tag{16}$$

where $x_i = \widehat{x}$ for $x = a_i, m_i$, and $c_{2,i} = \widehat{c_2}$, respectively. Note that regions invest into adaptation only, if the initial environmental quality, E, is below a critical level. That means, if the environmental quality is higher than this threshold, there is no need to undertake any climate protection investments.

Consider now stage 1 of the game. That means, given the optimal levels $\widehat{c_2}$ and $\widehat{a}$ each region i maximizes it's life-time utility function

$$\begin{aligned} U_i &= \alpha \ln(c_{1,i}) + (1-\alpha)\ln(E) \\ &+ \beta[\alpha \ln(\widehat{c_2}) + (1-\alpha)\ln(E + M + \widehat{a})], \end{aligned} \tag{17}$$

subject to the budget constraint

$$y_i = c_{1,i} + m_i + \frac{1}{1+r}s_i, \tag{18}$$

where $\beta \in (0,1)$ denotes the discount factor and where r is the exogenously given capital market interest rate.

Given the assumption that we are considering interior solutions only ,i.e. $c_{1,i} > 0$ and $m_i > 0$, maximizing (17) subject to (18) with respect to $c_{1,i}$ and m_i and inserting (15) implies the following first order conditions for consumption and mitigation, respectively

$$\frac{\alpha}{c_{1,i}} - \frac{\beta(1+r)}{e + M_{-i} - rm_i + (1+r)(y - c_{1,i})} = 0 \tag{19}$$

$$-\frac{\beta r}{e + M_{-i} - rm_i + (1+r)(y - c_{1,i})} = 0. \tag{20}$$

Obviously, if regions discount future well-being at a positive rate, and if the market rate of interest is strictly positive, i.e. $r > 0$, then the last optimality condition (20) is inconsistent with the assumption that $m_i > 0$. This implies a result which is almost completely in contrast to what we have observed in Section 3. Or formulated as a proposition:

Proposition 3 *If both the discount rates and the market rates of interest are strictly positive, the dynamic game has a unique equilibrium outcome where each country invests into adaptation only.*

In other words, regions spend their life-time income on consumption and adaptation only, but do not mitigate greenhouse gas emissions at all. Therefore under reasonable assumptions we observe the following optimal values for consumption, adaptation and environmental quality

$$\begin{aligned}
\widehat{c_1} &= \frac{\alpha((1+r)y + E)}{(\alpha+\beta)(1+r)} \\
\widehat{c_2} &= \frac{\beta\alpha((1+r)y + E)}{(\alpha+\beta)} \\
\widehat{a} &= \frac{(1-\alpha)(1+r)\beta y - (1+\beta)\alpha E}{(\alpha+\beta)} \\
\widehat{e} &= \frac{(1-\alpha)((1+r)y + E)\beta}{(\alpha+\beta)}.
\end{aligned}$$

Overall, this result is not too surprising. Our modeling reflects what is observed in reality. Costs of greenhouse gas mitigation are borne early, but benefits accrue in the distant future. This is in almost complete contrast to adaptation where benefits can be realized over the short term. Therefore, both the discount rate and the interest rate matter for two reasons. First, the present value of marginal benefits from investing one unit of conventional wealth into mitigation is $\frac{\beta}{(1+r)}$ which is less then one if $\beta < 1$ and $r > 0$. Thus, the higher the discount rate, the lower the present values of benefits of mitigation. Second, our analysis is based upon the assumption that (1) adaptation and mitigation are perfect substitutes, which is stated explicitly, and (2), that costs are the same, which is not expressed in terms of an assumption. This has, however, severe consequences. Since there is a time delay between investing into and receiving benefits of one period in the case of mitigation, but not in the case of adaptation, for receiving the same marginal benefits, the present value of investment into adaptation is $\frac{1}{1+r}$ which is smaller than one, and hence smaller than the present value of costs of mitigation. Consequently, it is optimal to invest into adaptation only, as long as the capital market interest rate is positive.

5 The Dynamic Game with Cost Extension

The last section analyzed the interaction between mitigation and adaptation within a dynamic framework where constant and equal marginal costs of mitigation and adaptation were assumed. The model is now extended by introducing different marginal costs of mitigation and adaptation. The dynamic setting of the game remains unchanged.

The rationale for assuming different marginal costs of adaptation and mitigation is the following: Mitigating emissions today increases future environmental quality, which in turn influences the need for adaptation in the future. Therefore, the higher today's mitigation effort by all countries, the better the environmental quality in the future, and thus, the less adaptation measures will be required to reduce climate damages in the future. Or to put it differently, the more mitigation is undertaken in the present, the lower the future costs of adaptation.

Furthermore, the costs of adaptation also depend on the present state of the environmental quality. The higher the initial environmental quality, the less adaptation effort will be needed in the future and therefore, the lower the costs of adaptation. Assumption 2 covers these interrelationships between costs of adaptation, overall mitigation effort and initial environmental quality.

Assumption 2 *For each country i let the costs of mitigation $c(m_i)$ and adaptation $c(a_i)$ be*

$$c(m_i) = \gamma m_i \qquad \textit{and} \qquad c(a_i) = \frac{\delta a_i}{E + M}$$

with parameters $\delta, \gamma > 0$.

Analogous to section 4, we now solve for the equilibrium using backward induction. Note that the assumption of different marginal mitigation and adaptation costs does not affect the objective function, though it changes the budget constraint of each country. Hence, in the second stage of the game every player i maximizes objective function (13) with respect to the budget constraint

$$s_i = c_{2,i} + \frac{\delta a_i}{E+M}. \tag{21}$$

Solving the maximization problem we obtain the optimal levels of adaptation and consumption for every country, which, because of symmetry between regions, read as follows

$$\begin{aligned} \tilde{a} &= (\frac{1-\alpha}{\delta}s - \alpha)(E+M) \\ \tilde{c_2} &= (\delta + s)\alpha. \end{aligned}$$

Because of symmetry let $x_i = \tilde{x}$ for $x = a_i, m_i, c_{1,i}, c_{2,i}$. Note that the optimal adaptation level for every region depends on the initial environmental quality and on the mitigation effort by all regions. For any initial environmental quality below a critical level, regions do not undertake any adaptation effort in the second stage.

Given every region's optimal decision concerning consumption and adaptation in the second stage of the game, each region then maximizes in the first stage it's life-time welfare

$$\begin{aligned} U_i &= \alpha \ln(c_{1,i}) + (1-\alpha)\ln(E) \\ &+ \beta[\alpha \ln(\tilde{c_2}) + (1-\alpha)\ln(E+M+\tilde{a})], \end{aligned} \tag{22}$$

subject to the budget constraint

$$y_i = c_{1,i} + \gamma m_i + \frac{1}{1+r}s_i. \tag{23}$$

By maximizing (22) subject to (23) with respect to $c_{1,i}$ and m_i, we obtain the optimal levels of consumption and mitigation:

$$\begin{aligned} \tilde{c_1} &= \frac{\alpha((1+r)(yn+\gamma E)+\delta n)}{(1+r)(\alpha n + \beta n + (1-\alpha)\beta)} \\ \tilde{m} &= \frac{(1+r)(1-\alpha)\beta y + (1-\alpha)\beta\delta - (1+r)(\alpha+\beta)\gamma E}{\gamma(1+r)(\alpha n + \beta n + (1-\alpha)\beta)}. \end{aligned}$$

Given the optimal levels of consumption and mitigation effort, which every region undertakes in the first stage, the optimal adaptation and consumption levels in the second stage then read as:

$$\tilde{a} = \frac{\beta(1-\alpha)((1+r)(E\gamma+yn)+\delta n)(\beta(1-\alpha)(1+r)(yn+E\gamma)-\delta((n-1)\beta\alpha+\alpha n+\beta))}{\delta(\beta\alpha-n\alpha-n\beta-\beta)^2\gamma(1+r)}$$

$$\tilde{c_2} = \frac{\beta\alpha((1+r)(yn+\gamma E)+\delta n)}{\alpha n+\beta n+(1-\alpha)\beta}.$$

Note that not only the optimal level of adaptation depends on the initial environmental quality E but also the level of mitigation. For any initial environmental quality below a critical value $\overline{E}$, i.e. $E < \overline{E}$, regions invest into mitigation, where

$$\overline{E} = \frac{(1-\alpha)\beta((1+r)y+\delta)}{\gamma(1+r)(\alpha+\beta)}. \tag{24}$$

And for any environmental quality above a critical level $\underline{E}$, i.e. $E > \underline{E}$, every region invests into adaptation, where

$$\underline{E} = \frac{\delta(n\beta\alpha-\beta\alpha+\alpha n+\beta)-(1-\alpha)(1+r)\beta ny}{\gamma\beta(1-\alpha)(1+r)}. \tag{25}$$

Thus, in optimum regions invest into mitigation as well as into adaptation if they face an initial environmental quality which lies between $\underline{E}$ and $\overline{E}$, i.e. for $E \in (\underline{E}, \overline{E})$.

Let us now look at the characteristics of this interval. As can be taken from (24) and (25) the range of the interval $(\underline{E}, \overline{E})$ depends on the life-time endowment y. This interval is for a region i only positive, i.e. $\overline{E} > \underline{E}$, if the life-time endowment y is greater than the critical value $\underline{y}$ with

$$\underline{y} = \frac{(1+\beta)\alpha\delta}{(1-\alpha)\beta(1+r)}.$$

In order to guarantee that $\underline{E} > 0$ we furthermore restrict the interval for regional life-time endowment y with the upper-bound $\overline{y}$, where

$$\overline{y} = \frac{\delta(n\beta\alpha+\alpha n+(1-\alpha)\beta)}{(1-\alpha)(1+r)\beta n}.$$

With these results and definitions at hand, we now summarize our results in the following proposition.

Proposition 4 *In the dynamic game assuming mitigation costs $c(m_i) = \gamma m$ and adaptation costs $c(a_i) = \frac{\delta a_i}{E+M}$, there is a unique equilibrium outcome where every region undertakes mitigation as well as adaptation, if $E \in (\underline{E}, \overline{E})$ and $y \in (\underline{y}, \overline{y})$.*

In the following, let us consider a region that disposes of a life-time income $y > \underline{y}$. And let us distinguish between two different environmental conditions:

- A: low environmental quality: E^A close to $\underline{E}$
- B: high environmental quality: E^B close to $\overline{E}$.

Even though, the initial environmental qualities in these two conditions differ, we consider two environmental conditions in which a region mitigates and adapts to climate change, i.e. $E^A, E^B \in (\underline{E}, \overline{E})$. Since future marginal costs of adaptation decrease with higher initial environmental quality adaptation is relatively less expensive in status B than in A. Hence, we can state the following corollary.

Corollary 1 *Every region that disposes of an income $y > \underline{y}$ undertakes more adaptation (less mitigation) in status B than in status A.*

This result is driven by the assumption that the higher the environmental quality, the lower the costs of adaptation. If the environmental quality is low, i.e. E close to $\underline{E}$, a region with $y > \underline{y}$ undertakes more mitigation (less adaptation) than in a status with a high initial environmental quality, i.e. E close to $\overline{E}$, because adaptation is relatively more expensive.

Let us now focus on the interrelationship between the life-time endowment y of a region and the interval of the initial environmental quality E. The exogenously given initial environmental quality has to lie within the interval $(\underline{E}, \overline{E})$ in order that countries invest into both mitigation and adaptation. This interval depends on the life-time endowment y. As y increases, the range of the interval increases, i.e. $\frac{\partial(\overline{E}-\underline{E})}{\partial y} > 0$. In other words, the higher a region's life-time income is, the larger the range for an initial environmental quality such that regions undertake mitigation as well as adaptation. Hence, if a region disposes of a relatively large life-time endowment, there exist relatively more potential initial environmental qualities for which a region undertakes mitigation as well as adaptation. Hence, we can formulate the following corollary.

Corollary 2 *The higher the life-time endowment a region disposes of, the larger the scope for a region to improve future environmental quality.*

Note that if $y = \underline{y}$ and if there exists an initial environmental quality $E = \underline{E}(= \overline{E})$ [6] a region does not undertake any climate protection actions. Regions with

[6]if $y = \underline{y} \Rightarrow \underline{E} = \overline{E}$

low life-time endowments neither mitigate nor adapt to climate change. Because of their low income, regions do not possess the *financial freedom* to consume and to invest into environmental protection measures at the same time.

6 Conclusions

In this paper, we investigate the strategic interactions of mitigation and adaptation choices by n identical, independent and selfish countries. We show that in a static framework where countries simultaneously decide on their mitigation and adaptation there is a continuum of equilibria. These equilibria can be Pareto ranked. The welfare comparison shows that mitigation is Pareto superior to adaptation. Adaptation only leads to Pareto inferior equilibria.

In a dynamic setting, where the different time characteristics of mitigation and adaptation are taken into account, only one equilibrium (equilibrium with zero mitigation) emerges if regions face a positive capital market interest rate.

Assuming that the costs of mitigation and adaptation differ that is assuming that the future costs of adaptation depend on the present environmental quality and on the mitigation efforts undertaken, i.e. the higher the initial environmental quality and the more mitigation is undertaken by all regions, the smaller the future costs of adaptation, there is a unique equilibrium outcome where regions choose to invest into both mitigation and adaptation.

The higher the lifetime income of a region, the larger the scope for actions to react to climate change. Furthermore, the better the present environmental quality, regions undertake relatively more adaptation effort than mitigation.

There are obviously many directions into which the present analysis can be extended. As one of the next steps, we plan to extend the model to allow for uncertainty. The uncertainty will refer to the occurrence of the mitigation benefits, since it might take decades until the mitigation actions undertaken benefit to the world. Conversely, the benefits of adaptation are not affected by uncertainty, since the benefits of adaptation may occur within a much shorter time span.

A further extension of the model will be to allow for asymmetric countries and asymmetric effects of climate change. One particular comparative statics exercise would be to keep country size the same and to let some countries form a coalition (like EU or countries subscribing to the Kyoto protocol) that jointly determines their mitigation and adaptation levels. One would expect mitigation to become more attractive in such a setting. The assumption that mitigation and adaptation are perfect substitutes could also be relaxed in future work.

In an infinite dynamic game, it may be possible to achieve better outcomes than those of the static or of a two-stage game, as suggested, e.g., Dutta and Radner (2004), Dutta and Radner (2006a) and Dutta and Radner (2006b). Adding adaptation to the action set of each player may make punishment in case of a deviation less harsh for those who punish a deviator, which all else equal would render better outcomes achievable. On the other hand, though, the option of adaptation exists also for the deviator who is being punished and thus renders punishment less severe. Therefore, the overall effect of allowing for adaptation is not clear a priori and requires separate analysis.

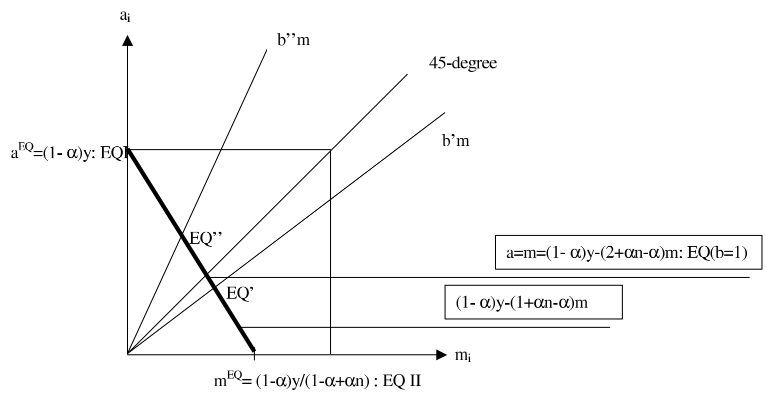

Figure 2: Proof of Proposition 2

Appendix

A Proofs

Proof of Proposition 1: Observe first that we have a system of n linear equations (7) with $2n$ unknowns: One equation and two choice variables (a_i, m_i) for each for each country i. Thus, the system is indeterminate, whence the multiplicity of solutions. In a symmetric equilibrium, $a_i = a$ and $m_i = m$ for all i. Thus, (7) becomes $m+a = (1-\alpha)y - \alpha(n-1)m$, which implies $a = (1-\alpha)y - (1-\alpha+\alpha n)m$, which is (8). As $m \geq 0$, the largest admissible a is $\overline{a}$. Similarly, $a \geq 0$ implies $m \leq \frac{(1-\alpha))y}{1-\alpha+\alpha n)} \equiv \overline{m}$. ■

Proof of Proposition 2: Any symmetric equilibrium (a^*, m^*) can be parameterized by a $b \in [0, \infty)$ so that $m^* = \frac{1-\alpha}{b+1+\alpha n-\alpha}y$ and $a^* = \frac{b-b\alpha}{b+1+\alpha n-\alpha}y$. Notice that $\frac{\partial m^*}{\partial b} < 0$ and $\frac{\partial a^*}{\partial b} > 0$. Figure 2 provides an illustration. A country's equilibrium consumption is $c^* = \frac{\alpha(n+b)}{1+b+\alpha n-\alpha}y$ and it enjoys environmental quality of $E^* = \frac{(1-\alpha)(b+n)}{1+b+\alpha n-\alpha}y$. It is straightforward to see that $\frac{\partial c^*}{\partial b} < 0$ and $\frac{\partial E^*}{\partial b} < 0$ for $n > 1$. ■

B Asymmetric Equilibria in the Static Game

This part of the Appendix contains a preliminary analysis of asymmetric equilibria in the static game. Even though we assume that all countries have the same CD preferences and the same income, there are many many equilibria that are not symmetric.

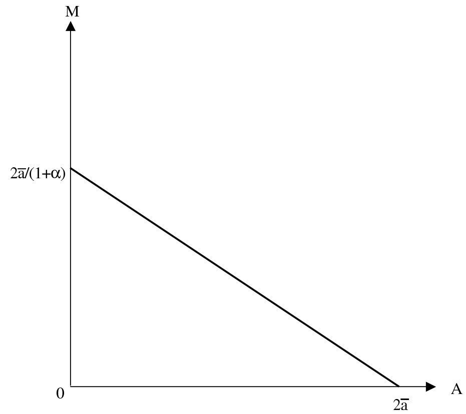

Figure 3: Equilibrium M and A.

To get an understanding of the problem, assume $n = 2$. The first order conditions for the two countries then are

$$m_1 + a_1 = \overline{a} - \alpha m_2 \tag{26}$$

$$m_2 + a_2 = \overline{a} - \alpha m_1 \tag{27}$$

The equilibrium values for m_i^* then satisfy

$$m_i^* = \frac{1}{1+\alpha}\overline{a} - \frac{1}{1-\alpha^2}a_i + \frac{\alpha}{1-\alpha^2}a_{-i}, \tag{28}$$

where $-i$ stands for "not i". The aggregate equilibrium level of mitigation is thus

$$M^*(A) = \frac{2\overline{a} - A}{1+\alpha}, \tag{29}$$

where $A \equiv a_1 + a_2$. Thus, the sums are uniquely determined; see Figure 3.

Assume now $m_2 = 0$. Then, all (a_1, m_1, a_2) satisfying

$$a_1 = \overline{a} - m_1 \tag{30}$$

$$a_2 = \overline{a} - \alpha m_1 \tag{31}$$

will be equilibria. Substituting $m_1 = \overline{a} - a_1$ we get

$$a_2 = (1-\alpha)\overline{a} + \alpha a_1$$

as the line that depicts the maximal amount of adaptation by 2 consistent with equilibrium. Doing the same for 1, i.e. assuming $m_1 = 0$, we get

$$a_1 = (1-\alpha)\overline{a} + \alpha a_2.$$

The set of equilibrium values for a_1 and a_2 is illustrated in Figure 4.

Next, we determine the boundaries for the equilibrium values of m_i. In order to do so, set $a_1 = 0$. Then, we get $m_1 = \overline{a} - \alpha m_2$ as the maximal amount of mitigation

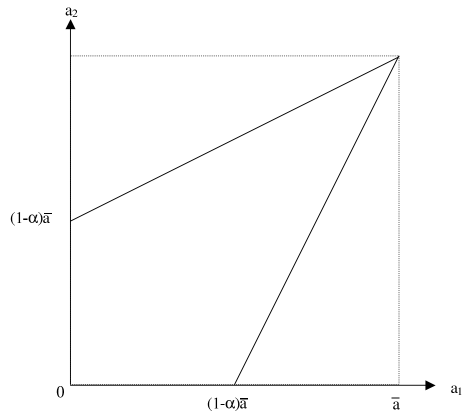

Figure 4: Equilibrium a_1 and a_2.

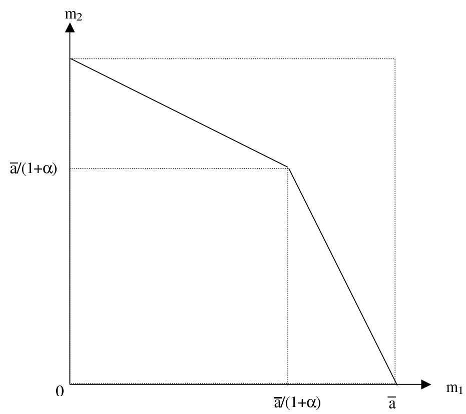

Figure 5: Equilibrium m_1 and m_2.

by 1 as a function of 2's mitigation. Similarly, for $a_2 = 0$, we get $m_2 = \overline{a} - \alpha m_1$. Figure 3 provides an illustration.

The hardest thing is to show how points in Figure 2 connect to those in Figure 5. Consider e.g. the point $(\overline{a}, \overline{a})$ in Figure 2. Clearly, the only consistent point with this one is (0,0) in Figure 3. Though right now I do not have a graphical solution, it seems clear that for any given point $a = (a_1, a_2)$ there is a unique corresponding point (m_1, m_2) given by equations (26) and (27).

Denote by $F(M)$ and $F(A)$, respectively, the size of the areas M and A. Then,

$$F(M) = \overline{a}^2 - 2(\overline{a} - \overline{m})\frac{\overline{a}}{2} = \overline{am} = \frac{1}{1+\alpha}\overline{a}^2$$

and

$$F(A) = \overline{a}^2 - 2(\overline{a} - (1-\alpha)\overline{a})\frac{\overline{a}}{2} = (1-\alpha)\overline{a}^2.$$

Thus, $F(M) > F(A)$, so that there appear to be "more" equilibrium points in M than in A. [TO BE COMPLETED]

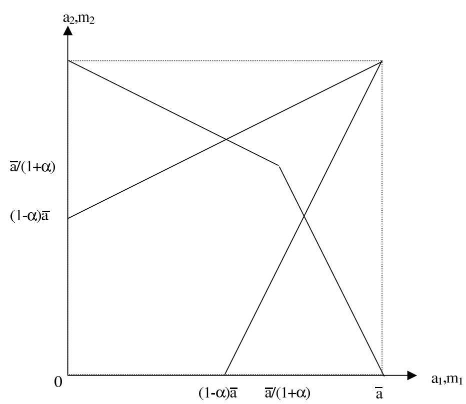

Figure 6: Equilibrium a_1 and a_2 and m_1 and m_2.

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