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Adaptation, Mitigation and Risk-Taking in Climate Policy

Heike Auerswald
Kai A. Konrad
Marcel Thum

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Abstract

The future consequences of climate change are highly uncertain. Today, the exact size of possible future damages are widely unknown. Governments try to cope with these risks by investing in mitigation and adaptation measures. Mitigation aims at a reduction of greenhouse gas emissions whereas adaptation reduces the follow-up costs of climate change. In contrast to the existing literature, we explicitly model the decision of risk-averse governments on mitigation and adaptation policies. Furthermore we also consider the interaction of the two strategies. Mitigation efforts of a single country trigger crowding out as other countries will reduce their mitigation efforts. We show that, under fairly mild conditions, a unilateral increase in mitigation efforts of a single country can even increase global emissions. In contrast, a unilateral commitment to large adaptation efforts benefits the single country and may reduce the global risk from climate change at the expense of other countries.

JEL-Code: Q540, Q580.

Keywords: climate change, adaptation, mitigation, risk-taking.

Heike Auerswald
Technical University Dresden
Faculty of Business and Economics
Germany – 01062 Dresden
heike.auerswald@tu-dresden.de

Kai A. Konrad
Max Planck Institute
Marstallplatz 1
Germany – 80539 Munich
kai.konrad@tax.mpg.de

Marcel Thum
Technical University Dresden
Faculty of Business and Economics
Germany – 01062 Dresden
marcel.thum@tu-dresden.de

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1 Introduction

Climate change is one of the major global policy issues and has been on the policy agenda for more than two decades. The consensus view nowadays predicts an average increase in global temperature of at least 4 degrees centigrade and up to 6 degrees centigrade until the end of this century, if no measures are taken to reduce greenhouse gas (GHG) emissions [IPCC (2007)]. Many prominent studies on the welfare effects of climate change come up with significant cost estimates for the global economy.[1] The majority of researchers also agree that there is considerable uncertainty about the magnitude of damages. This uncertainty rapidly increases when the temperature hike exceeds the 3-degree-centigrade threshold. For this scenario, current estimates of the welfare effects range from slight gains to losses of more than 10 percent of world GDP [Tol (2010), Aldy et al. (2010)]. Even though the large uncertainty is frequently mentioned, e.g. by Aldy et al. (2010), the endogeneity of the distribution of climate risk is hardly ever taken into account when analyzing the effects of climate policy. Climate policy affects both the size and dispersion of future damages from climate change. The present paper reveals that the risk dimension of climate policy has major implications for the role of commitment on unilateral advances and thus for the non-cooperative climate policy game.

To cope with the potential welfare costs of climate change, two types of measures are available: mitigation and adaptation. Mitigation aims at a reduction of global GHG emissions, whereas adaptation limits damages induced by climate change. An important difference between the two strategies is that mitigation efforts are contributions to a global public good (no one can be excluded from potential benefits) and adaptation is a private or local public good with spatially limited effects.

For years now, governments and politicians have tried to implement a global climate treaty to limit GHG emission without much success so far. To address this problem, unilateral advances in mitigation are frequently advocated by the media, environmentalists and the public. The main argument claims that advances in mitigation efforts will force other countries to imitate the unselfish behavior and thus lead to a more favorable scenario of climate change. Economists, in contrast, have frequently argued that unilateral measures of mitigation policy may simply crowd out mitigation efforts by other players and would therefore not be very successful. In absence of a global agreement or a (benevolent) world government, climate policy is made by individual countries in a non-cooperative setting. Besides individual incentives, the reactions of all other players have to be taken into account and countries strategically set their climate policy [BMF (2010)].

[1] For recent surveys, see Tol (2009), Tol (2010) and Aldy et al. (2010).

This type of analysis is often carried out within the framework of a public goods game with private provision. The nature and the comparative static properties of this game have been analyzed by Bergstrom, Blume and Varian (1986). Hoel (1991) applied this framework in the context of international climate policy. His seminal analysis of unilateral action in global environmental problems shows that a commitment on unilateral advances changes the equilibrium outcome: the unilateral advances are partially crowded out due to the reduced equilibrium efforts of the other contributors.[2] Other forms of strategic behavior have also been studied. For instance, countries may prefer to remain uninformed about their country-specific benefits from a public good [Morath (2010)]. This underinvestment helps them to commit to a low level of public good contribution while all other countries are worse off. The role of endogenous uncertainty and information has also received some attention. Robledo (1999) considers whether risk averse players may abstain from purchasing insurance, because the exposure to the risk provides a strategic benefit in a future game of voluntary contributions to a public good.[3]Kane and Shogren (2000) consider climate policy as a choice of risk-taking, without consideration of the strategic effects for the equilibrium interaction in the non-cooperative equilibrium.[4]

We reconsider the initial crowding-out argument and take into consideration how environmental risk and risk aversion of governments affect its relevance. Advocates of a more pronounced mitigation policy with precommitment often claim that the economists' argument fails to fully take into account the risks of climate change. In fact if it is not only the total (expected) payoff that matters but also its riskiness, the individual contribution to the global public good and also the crowding out may be quite different. This argument is given a closer scrutiny here, assuming that the representative citizens are risk-averse and represented by a benevolent government in each country. National governments decide on the individual amount of miti-

[2] In an experimental setting, Sturm and Weimann (2004) confirm Hoel's result, when countries decide simultaneously on the public good contribution. Numerous other extensions have been developed, e.g. Vicary (2009) modifies the model for explaining what drives non-cooperative mitigation policy with respect to asymmetries between countries.

[3] There is a broad literature on further strategic aspects in the private provision of public goods. These include Konrad (1994), Ihori (1996), Buchholz, Nett and Peters (1998) and Siqueira (2003).

[4] Of course, the risk dimension plays a crucial role in many contributions to climate change. However, the uncertainty is rarely included in the objective function of the decision maker. Ingham, Ma and Ulph (2007) regard uncertainty as a lack of knowledge and examine the effects of future learning on climate policy. Tol and Yohe (2007) focuses on expected cost-benefit analysis and its applicability when damages are highly uncertain using the integrated assessment model *FUND* (Climate Framework for Uncertainty, Negotiation and Distribution). Hasson, Löfgren and Visser (2010) include uncertainty about climate change in an experimental setting by adding a stochastic risk component to test whether participants contribute more in high-vulnerability treatments.

gation efforts and thus influence the global public good 'GHG emission reduction'. The magnitude of climate change then affects the size and riskiness of damages in a country. Thus, mitigation policy acts as a self-insurance device [Ehrlich and Becker (1972)].

The contributions to the public goods literature that are structurally closest to ours are Ihori and McGuire (2007), Ihori and McGuire (2010), and, in particular, Lohse, Robledo and Schmidt (2010). These contributions consider voluntary contributions to a group public good, with the public good being self insurance (the sum of contributions reducing the size of the loss) and/or being self protection (the sum of contributions reducing the probability of a loss). Ihori and McGuire (2007) analyze the importance of group size in this framework. Lohse, Robledo and Schmidt (2010) characterize the welfare optimum, consider existence and properties of the non-cooperative equilibrium, and the interaction with market insurance in an expected utility framework. These analyses show the importance of income effects of contributions by others and how they interact with decreasing or increasing absolute risk aversion in a player's contribution decision. Thereby they uncover an important mechanism that is also driving the results in our framework. We use a mean-variance approach, such that the difference between self-insurance and self-protection becomes less pronounced, and ask the policy question about the strategic implications of a unilateral commitment on advances.

Our analysis proceeds in three steps. First, we derive the optimal amount of mitigation from the point of view of a single risk-averse country given the mitigation efforts of all other countries. We show how the contribution to the global public good varies with the wealth of a country and its exposure to climate change. And – most importantly – we show that risk considerations cause an even more pronounced crowding-out effect. Under fairly mild conditions, the unilateral advance of a single country in mitigation policy induces policy changes in the rest of the world such that total mitigation efforts are reduced. Intuitively, the additional mitigation effort works much like an income transfer to the rest of the world. The increase in income makes the other countries more willing to bear risks. Hence, they reduce their own mitigation efforts. In the end, the unilateral advance can lead to more global risks in the aggregate. Second, we derive the Nash equilibrium and characterize its properties if all countries contribute to the global public good. The equilibrium analysis confirms that unilateral advances away from the Nash equilibrium can be strongly counterproductive. Third, we consider adaptation as an alternative climate policy strategy. Adaptation limits the local damages from climate change and is therefore, by assumption, a substitute measure for self-insurance. The focus on adaptation in climate policy is beneficial for a single country not only because it reduces the risk from climate change, but also because it affects the behavior of other countries. The early commitment to significantly large adaptation efforts acts as a credible promise that this country will exert low mitigation efforts in the future. This, in turn, forces the other countries to pursue more ambitious mitigation goals.

The paper is structured as follows: section 2 discusses the contributions to global mitigation in a model with risk-taking behavior. In section 3, we extend the model by also allowing for adaptation as a second strategy of climate policy. Section 4 concludes.

2 Mitigation Policy Only

2.1 A Country's Individually Optimal Choice

For the moment, we will focus on the climate policy of a single country or region and denote this region with index 1, whereas the rest of the world is labeled "country 2". In a strategic context, we treat country 2 as one single player for simplicity reasons.[5] Global CO_2 emissions determine the well-being in the world as they are causal for climate change.[6] Country 1 faces the risk of a stochastic net damage (loss) L_1 from climate change with mean $\bar{\mu}_1$ and standard deviation $\bar{\sigma}_1$. This stochastic damage can be influenced by investing in mitigation policies. If country 1 invests m_1 and the rest of the world invests m_2 in mitigation, the effective damage becomes $\alpha(m) \cdot L_1$ with $m = m_1 + m_2$. Hence, mitigation is a global public good, since the quality of the public good depends on the contributions of all countries.

Some regularity assumptions about α are as follows: we assume that the function α is twice continuously differentiable, decreasing in additional mitigation, but at a decreasing rate $[\frac{\partial \alpha(m)}{\partial m} \equiv \alpha_m \leq 0]$ and $[\frac{\partial^2 \alpha(m)}{(\partial m)^2} \equiv \alpha_{mm} \geq 0]$. The first dollar spent on climate policy is highly productive $[\frac{\partial \alpha(m)_{m=0}}{\partial m} = -\infty]$ and beyond a certain threshold $\bar{m}$, additional measures do not further reduce damages from climate change $[\frac{\partial \alpha(m)}{\partial m} = 0]$ for all $m \geq \bar{m}$. Mitigation comes at a cost. We assume a twice continuously differentiable and convex cost function $c(m_1)$ with $c_m \geq 0$, $c_{mm} > 0$ and $c(0) = c_m(0) = 0$. Let y_1 be the initial wealth of country 1. The country can influence the size and riskiness of the stochastic final wealth V_1 by choosing the appropriate mitigation measures:

$$V_1 = y_1 - c(m_1) - \alpha(m) \cdot L_1. \tag{1}$$

Country 1 is populated by a representative risk-averse individual that has preferences

[5] This simplifies the analysis considerably and allows us to study the strategic context. Evidently it disregards the fact that some countries in the rest of the world may be in a corner solution, and also the strategic interaction between them.

[6] Throughout the paper, we use CO_2 as an example of greenhouse gases.

over the mean and the standard deviation of domestic wealth, represented by a twice continuously differentiable utility function $U(\mu_1, \sigma_1)$, where μ_1 denotes the mean and σ_1 the standard deviation of final wealth. The utility function has the usual properties $U_\mu > 0$, $U_\sigma < 0$, $U_{\mu\mu} < 0$ and $U_{\sigma\sigma} < 0$.[7]

We can now analyze the climate policy of a single country that maximizes the utility of a representative citizen. For the moment, we take m_2, the mitigation efforts in the rest of the world, as given and focus solely on country 1, which faces the following maximization problem:

$$\begin{aligned} \max_{m_1} \quad & U(\mu_1; \sigma_1) \\ \text{with} \quad & \mu_1 = \quad y_1 - c(m_1) - \alpha(m_1 + m_2) \cdot \bar{\mu}_1 \\ & \sigma_1 = \quad \alpha(m_1 + m_2) \cdot \bar{\sigma}_1 \end{aligned} \tag{2}$$

Mitigation reduces the riskiness $[\sigma_1]$ of damages induced by climate change, but has an ambiguous effect on the expected wealth $[\mu_1]$. While the expected damage is reduced, mitigation is also associated with costs. Domestic climate policy has to balance these countervailing effects by choosing an appropriate contribution to global mitigation efforts.

The first-order condition is

$$\text{FOC:} \qquad f^m \equiv U_\mu \mu_{m_1} + U_\sigma \sigma_{m_1} = 0 \tag{3}$$

where μ_{m_1} and σ_{m_1} are the derivatives of mean and standard deviation with respect to m_1. The second-order condition is given by $f^m_m \equiv \frac{\partial f^m}{\partial m} < 0$. Rearranging the first-order condition yields the first results of our analysis:

$$\left.\frac{d\mu_1}{d\sigma_1}\right|_{\bar{U}} = -\frac{U_\sigma}{U_\mu} = \frac{\mu_{m_1}}{\sigma_{m_1}}. \tag{4}$$

The left-hand side of equation (4) describes the marginal rate of substitution between expected wealth and risk. It tells us how much additional expected wealth is needed to compensate the representative individual for a slight increase in the standard deviation. The right-hand side captures the marginal rate of transformation. Country 1 has to give up some expected wealth through mitigation to reduce the risk of damages from climate change. In the optimum, the marginal rate of substitution and the marginal rate of transformation are equalized.

[7] As all distributions in the choice set belong to the same linear class, the mean-variance-approach is equivalent to the expected utility approach; see MEYER (1987) and SINN (1989). The latter also contains a comprehensive treatment of the mean-variance-approach.

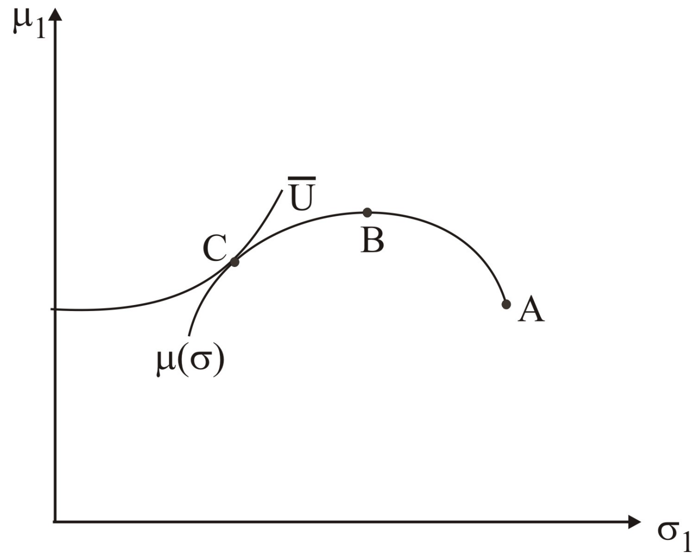

Figure 1: Optimal climate policy for country 1

The outcome is illustrated in Figure 1. The $\mu(\sigma)$-curve describes the efficiency frontier of the opportunity set in country 1 for a given mitigation policy m_2 in the rest of the world. All points beneath the curve are also feasible but inefficient; all points above are not attainable. The slope of this curve equals the marginal rate of transformation [see equation (4)]:

$$\frac{\mu_{m_1}}{\sigma_{m_1}} = \frac{-c_m(m_1) - \alpha_m \cdot \bar{\mu}_1}{\alpha_m \cdot \bar{\sigma}_1}. \tag{5}$$

Without any investments ($m_1 = 0$), the economy is situated at point A. The first dollar invested in mitigation is highly productive, whereas the marginal cost is zero. The slope of the efficiency frontier in A amounts to $-\frac{\bar{\mu}_1}{\bar{\sigma}_1}$. Starting to invest in mitigation, the mean wealth increases and the standard deviation is reduced. When the productivity of further investments becomes sufficiently small (beyond point B), the reduced risk comes at the cost of a lower expected wealth. As the slope of the indifference curve $\bar{U}$ corresponds to the marginal rate of substitution, the optimal climate policy for country 1 is reached when the indifference curve becomes tangent to the opportunity set (point C). Note that the position of the efficiency frontier changes when m_2 varies. How changes in m_2 effect the opportunity set of country 1 is discussed in the next section.

How does the domestic policy react to changes in the exposure to risk? Will countries with larger expected damages and larger risk also spend more on mitigation measures? We carry out a comparative static analysis of mitigation efforts with respect to $\bar{\mu}$ and $\bar{\sigma}$. To obtain the reaction in domestic mitigation measures to increasing expected losses, we differentiate equation (3) with respect to $\bar{\mu}_1$ and m_1

and get:

$$\frac{dm_1}{d\bar{\mu}_1} = \frac{[U_{\mu\mu}\mu_{m_1} + U_{\mu\sigma}\sigma_{m_1}] \cdot \alpha + U_\mu \cdot \frac{\partial \alpha}{\partial m}}{f^m_m}. \tag{6}$$

Using the first-order condition (3) to replace μ_{m_1}, we obtain

$$\frac{dm_1}{d\bar{\mu}_1} = \frac{\{[U_{\mu\sigma} \cdot U_\mu - U_{\mu\mu} \cdot U_\sigma] \cdot \frac{\sigma_1}{U_\mu} + U_\mu\}\frac{\partial \alpha}{\partial m}}{f^m_m}. \tag{7}$$

Note that U_μ is positive; $\frac{\partial \alpha}{\partial m}$ and f^m_m are both negative. Hence, the overall sign of equation (7) depends on the term in square brackets, which describes the absolute risk aversion of the representative individual (see Appendix A.1). The individual has a decreasing (increasing) absolute risk aversion if the term in square brackets is positive (negative). Therefore, a country reacts to increasing expected climate damages with an increase in mitigation measures as long as absolute risk aversion does not increase too strongly.

In a next step, we analyze the impact of a larger risk $\bar{\sigma}_1$ on mitigation efforts. Applying the same procedure as before yields, after some manipulation,

$$\frac{dm_1}{d\bar{\sigma}_1} = \frac{\{S + \frac{\partial S}{\partial \sigma_1} \cdot \sigma_1\} \cdot U_\mu \cdot \frac{\partial \alpha}{\partial m}}{f^m_m}. \tag{8}$$

with $S \equiv \left.\frac{d\mu_1}{d\sigma_1}\right|_{\bar{U}}$ describing the slope of the indifference curve. The slope S is positive and will increase in σ_1 if the absolute risk aversion is not increasing too strongly. Hence, for the plausible cases of constant or decreasing absolute risk aversion, mitigation efforts increase with rising risks from climate change.

Proposition 1. For constant and decreasing absolute risk aversion, the mitigation efforts of a country will rise with (i) its expected damage $[\bar{\mu}_1]$ and (ii) its risk exposure $[\bar{\sigma}_1]$.

Finally, we can also carry out the comparative statics with respect to a country's initial wealth. The question is whether mitigation policies of richer countries differ from those of poorer countries. Differentiating equation (3) with respect to y_1 and m_1 leads to

$$\frac{dm_1}{dy_1} = -\frac{[U_{\sigma\mu}U_\mu - U_{\mu\mu}U_\sigma] \cdot \frac{\sigma_{m_1}}{U_\mu}}{f^m_m}. \tag{9}$$

Again, the effect depends on the term in square brackets. Assuming decreasing absolute risk aversion, the term will be positive and mitigation measures decrease in y_1. If a country gets richer, its willingness to invest in mitigation will go down.

Proposition 2. With decreasing absolute risk aversion, the mitigation efforts depend negatively on a country's initial wealth.

In the standard models of private provision of public goods, the contribution to a public good rises with income (if the public good is normal). In our case, the rise in income makes the representative individual marginally less risk averse and in consequence leads to a lower contribution.

2.2 Unilateral Advances in Mitigation Policy

Unilateral advances in climate policies are frequently advocated by the media, environmental activists and the public. Politics is pressured to go ahead with mitigation policies. The main argument is that advances in climate policies will induce other countries to imitate this behavior and thus lead to a more favorable scenario of climate change. In this section, we analyze the consequences of unilateral advances in mitigation policy for global mitigation efforts and for global risk-taking. How does country 1 adjust its mitigation policy if country 2 exogenously increases expenditures on mitigation? Again, using the first-order condition (3), we can evaluate the impact of changes in m_2 on mitigation in country 1. Differentiating yields the following comparative statics

$$\frac{\partial m_1}{\partial m_2} = -\frac{\frac{\partial f^m}{\partial m_2}}{f^m_m}. \tag{10}$$

The relevant question here is whether country 1 will fully or partially crowd out the additional mitigation efforts by other countries. We can rewrite equation (10) as

$$\frac{\partial m_1}{\partial m_2} = -\frac{f^m_m + \overbrace{[U_{\mu\sigma}U_\mu - U_{\mu\mu}U_\sigma] \cdot \frac{\sigma_m}{U_\mu} \cdot c_m}^{A} + \overbrace{c_{mm} \cdot U_\mu}^{B}}{f^m_m} \tag{11}$$

(see Appendix A.2). As $f^m_m < 0$ shows up in the numerator and denominator, the overall effect depends on the second and third term in the numerator denoted by A and B. If both terms sum up to zero, we have perfect crowding out ($\frac{\partial m_1}{\partial m_2} = -1$). If $A + B$ becomes negative, the reduction in mitigation effort of country 1 even overcompensates the additional efforts of the other country ($\frac{\partial m_1}{\partial m_2} < -1$); total mitigation efforts are reduced.

Taking a closer look, the sign of term A depends on the degree of absolute risk aversion captured by the term in square brackets.[8] Again, for constant absolute

[8] Note that $\sigma_m < 0$, $U_\mu > 0$ and $c_m \geq 0$.

risk aversion it becomes zero and for decreasing absolute risk aversion it becomes positive (see Appendix A.1). Term B, finally, is always positive due to the convexity of the cost function.

Proposition 3. With constant or increasing absolute risk aversion, a unilateral increase in the mitigation effort of other countries is only partly crowded out by the reduced efforts of country 1. If, however, the absolute risk aversion is sufficiently decreasing, the increased mitigation efforts of other countries are more than crowded out.

Under the plausible condition of decreasing absolute risk aversion, unilateral increases in mitigation efforts by a single country may be counterproductive. In contrast to the standard models of public contributions, a unilateral increase in investment can be more than crowded out so that global mitigation even decreases. The explanation for this seemingly paradoxical result is the wealth effect created by the unilateral mitigation efforts.

The different effects are illustrated in Figure 2. The unilateral efforts of the other country shift up the opportunity set of country 1. For each risk σ_1, country 1 now achieves a higher expected wealth as the costs of mitigation are now borne to a larger extent by the other country. In addition to the shift upward, the slope of the efficiency frontier changes. This can be seen from equation (5). For each level of σ_1, the slope of the efficiency curve is lower, since the marginal cost to achieve σ_1 has fallen. Whether country 1 wants to select a lower or higher risk depends furthermore on the risk preferences. For constant absolute risk aversion, the slope of the indifference curve $\bar{\mathrm{U}}$ remains constant for a given level of σ_1 (e.g., when moving from C to C'). If relative risk aversion is strongly decreasing, the flattening of the indifference curve will be stronger than the flattening of the efficiency frontier. Then a tangency point to the right of C' is chosen. In this case, country 1's expected wealth increases but the risk has become larger too. In the next section, we study whether this seemingly paradoxical result can also survive in the Nash equilibrium.

2.3 The Non-Cooperative Equilibrium in Mitigation

So far, we have focused on the decisions of a single country and its reactions to a change in country 2. We now turn to the equilibrium in which both countries' choices are determined endogenously. In the absence of a (benevolent) world government and of binding global climate agreements, these contributions are made in a non-cooperative setting. Each region decides on its privately optimal mitigation level – given the mitigation efforts of the other country. The Nash equilibrium of the

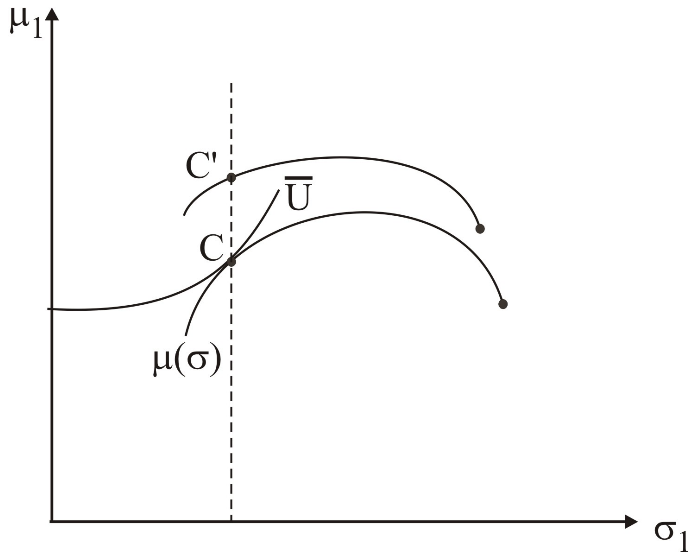

Figure 2: Country 1's response to unilateral mitigation efforts

mitigation game is then a vector of contributions (m_1^*, m_2^*) where each m_i^* is the best response to m_j^* fulfilling equation (3) $[i, j = 1, 2; i \neq j]$.

Proposition 4. The Nash equilibrium of mitigation efforts has the following properties: (a) There is at least one stable interior equilibrium in pure strategies. (b) The excessive crowding out $[\frac{\partial m_i}{\partial m_j} < -1$ with $i, j = 1, 2]$ can only occur in an asymmetric equilibrium.

Proof. (a) Consider the reaction functions $m_1(m_2)$ and $m_2(m_1)$. Each intersection of these reaction functions is a Nash equilibrium, denoted (m_1^*, m_2^*). The reaction functions are continuous self-mappings on the closed and compact set $[0, \bar{m}]$. Hence, these functions intersect at least once. This proves that a Nash equilibrium exists. We can rule out $m_i^* \geq \bar{m}$ for $i \in \{1, 2\}$ by the following reasoning: i's utility is higher for $m_i = \bar{m}$ than for $m_i > \bar{m}$. Moreover, a marginal reduction in effort at $m_i = \bar{m}$ increases i's utility since this reduction has a positive first-order effect on μ_i, but a zero first-order effect on σ_i. This result, in turn, can be used to rule out $m_i^* = 0$. Consider a marginal increase in m_i at $m_i = 0$. As $m_j^* < \bar{m}$, this increase has a strictly beneficial first-order effect on σ_i and a non-negative first-order effect on μ_i. This shows that at least one interior equilibrium exists. Further, by the same arguments, $0 < m_i(m_j) < \bar{m}$ for all $m_j \in [0, \bar{m}]$, and $\lim_{m_j \to \bar{m}} m_i(m_j) = 0$. Accordingly, the curve $m_1(m_2)$ starts above $m_2(0)$ in figure 3, and must, at some point, fall below $m_2(m_1)$. Hence, at the intersection, the stability condition $\frac{\partial m_1}{\partial m_2} \cdot \frac{\partial m_2}{\partial m_1} < 1$ must be fulfilled. (b) The statement is a corollary of (a): If both countries are symmetric, then the reaction functions are mirror images. The number of equilibria must be

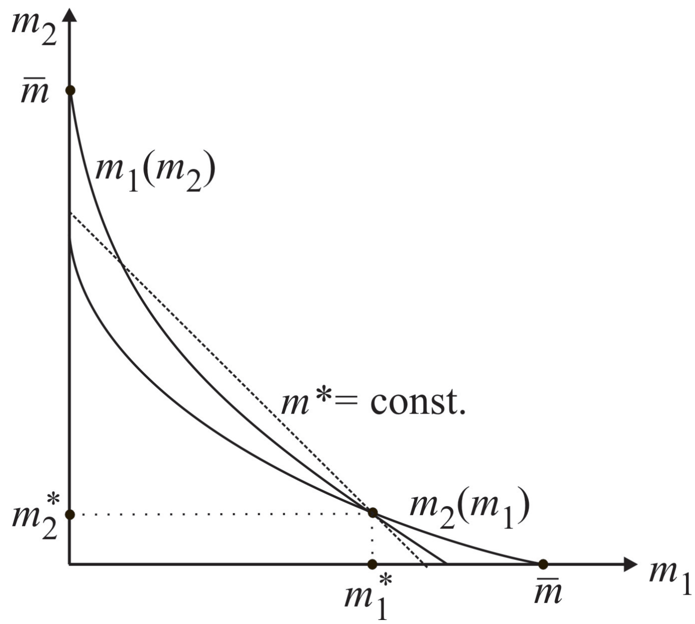

Figure 3: The Nash equilibrium in mitigation efforts with asymmetric countries

uneven. Hence, the symmetric equilibrium must be one in which $m_1(m_2)$ intersects $m_2(m_1)$ from the upper left to the lower right. As a consequence of symmetry, we observe less than full crowding out as $|\frac{\mathrm{d}m_i}{\mathrm{d}m_j}| < 1$. However, as shown in figure 3, more than full crowding out may occur in the case of asymmetric countries. To the left of the Nash equilibrium, both reaction curves are located beneath the dashed line (m^*= const.), which denotes all mitigation efforts m_1 and m_2 generating the same total mitigation level as in the Nash equilibrium (m_1^*, m_2^*). If country 2 unilaterally increases its mitigation efforts by one unit, the stability condition $\frac{\partial m_1}{\partial m_2} \cdot \frac{\partial m_2}{\partial m_1} < 1$ holds but global mitigation decreases when unilateral advances are made.■

Without further specifying the functional forms, it is impossible to say whether the equilibrium is unique. However, if there are $2n + 1$ equilibria, at least $n + 1$ of them must be stable.

Proposition 4 shows that the seemingly paradoxical effect of more than crowding out can survive in the neighborhood of a Nash equilibrium. It requires that one country reacts very flexibly to changes in mitigation, whereas the other country has to react little. Within the context of actual climate policy, this need not be a strong assumption. In the standard Bergstrom, Blume and Varian (1986) framework of private provision of a public good, only partial crowding out (or full crowding out as a limiting case) is possible. Hence, in this framework generous unilateral self-commitment to reduce emissions by more than the equilibrium amount may be costly for the country that makes this commitment, but overall it has a (possibly small but) positive effect for the environment overall. The result of excessive crowding out that can emerge in the context of uncertain environmental damages shows that the overall effect for climate policy can even be negative. Hence, uncertainty and risk aversion strengthen the policy arguments against generous commitments for unilateral emission reductions.

3 Adaptation as an Additional Instrument in Climate Policy

As we have just seen, unilateral advances in mitigation may not work in a non-cooperative setting. In the extreme case, the additional efforts of a single country are more than crowded out by the other country. If unilateral advances in mitigation do not work, maybe an alternative strategy using adaptation can help to improve global risk-taking. Adaptation comprises all measures that reduce the damages from climate change (e.g, higher dams or more stable buildings as a protection against extreme weather events).[9] In a first step, we extend our model by allowing for adaptation as an additional instrument for domestic climate policy. For the purpose of clarity, we start out again with the partial equilibrium approach and focus solely on a single country, which uses adaptation in a non-strategic manner. In a second step, we allow one country to use adaptation as a strategic instrument. We analyze how the Nash equilibrium is affected when one country can commit to an adaptation policy before the mitigation game is played.

3.1 The Optimal Mix of Adaptation and Mitigation

We extend our base model to allow for adaptation efforts in addition to mitigation. If country 1 invests m_1 in mitigation and a_1 in adaptation, the effective damage from climate change becomes $\alpha(a_1, m) \cdot L_1$ with $m = m_1 + m_2$. While mitigation is a global public good, adaptation is a private good. We assume that adaptation has the same qualitative impact on α as mitigation, i.e. $\alpha_a \leq 0$ and $\alpha_{aa} > 0$ and can thus be seen as a perfect substitute to mitigation. The cost of adaptation is denoted by $k(a_1)$ with $k_a \geq 0$, $k_{aa} > 0$ and $k(0) = k_a(0) = 0$. Country 1 now faces

[9] For a more detailed distinction between different types of adaptation, see for example Fankhauser, Smith and Tol (1999). An alternative classification of adaptation measures is given by Ingham, Ma and Ulph (2007).

a stochastic final wealth of

$$\begin{aligned} V_1 &= y_1 - k(a_1) - c(m_1) - \alpha(a_1, m) \cdot L_1 \\ \text{with} \quad \mu_1 &= y_1 - k(a_1) - c(m_1) - \alpha(a_1, m) \cdot \bar{\mu}_1 \\ \text{and} \quad \sigma_1 &= \alpha(a_1, m) \cdot \bar{\sigma}_1 \end{aligned}$$

Maximizing utility $U(\mu_1, \sigma_1)$ of the representative individual with respect to m_1 and a_1 yields

$$f^a \equiv U_\mu \mu_{a_1} + U_\sigma \sigma_{a_1} = 0 \tag{12}$$

$$f^m \equiv U_\mu \mu_{m_1} + U_\sigma \sigma_{m_1} = 0 \tag{13}$$

which leads to the optimality condition

$$\left.\frac{d\mu_1}{d\sigma_1}\right|_{\bar{U}} = -\frac{U_\sigma}{U_\mu} = \frac{\mu_{m_1}}{\sigma_{m_1}} = \frac{\mu_{a_1}}{\sigma_{a_1}}. \tag{14}$$

Hence, the marginal rate of substitution has to be equal to the marginal rate of transformation of both adaptation and mitigation.[10] Substituting the derivatives of μ_1 and σ_1 and simplifying provides some insights into the optimal mix of adaptation and mitigation:

$$-\frac{c_m}{\alpha_m \cdot \bar{\sigma}_1} = -\frac{k_a}{\alpha_{a_1} \cdot \bar{\sigma}_1}. \tag{15}$$

Country 1 should choose adaptation and mitigation in a way such that the marginal cost per unit of risk reduction is the same across the two policy instruments.

Proposition 5. From the point of view of a single country, climate policy will be chosen optimally if (i) the marginal rate of substitution between μ and σ equals its marginal rate of transformation and if (ii) the marginal cost of adaptation and mitigation per unit of risk reduction are equalized.

Adaptation creates only local benefits but it is nevertheless linked to the global mitigation efforts. As mitigation and adaptation are substitutes with respect to risk reduction, a country will also adjust its adaptation policy in the wake of additional mitigation efforts of the rest of the world. We discuss this strategic interaction between mitigation and adaptation in the next section.

[10] The second-order conditions are in Appendix A.3.

3.2 Adaptation as a Commitment Device

Suppose that country 1 can credibly commit to a certain amount of adaptation measures. Later, both countries 1 and 2 play the contribution game with respect to mitigation efforts.[11] The early commitment will influence the mitigation efforts of the other country. In the following, we analyze whether country 1 has an incentive to use such a commitment strategy. We also discuss under which conditions global risks from climate change will be reduced.

We reformulate our model as a two-stage game. In stage 1, country 1 commits to adaptation $\bar{a}_1$. In stage 2, the mitigation game is played as described in section 2. Solving by backward induction, we start in the second stage, where each country i chooses its own contribution m_i for a given contribution of the other country and for a given level of adaptation of country 1 ($\bar{a}_1$). The first-order condition for country 1 is

$$U_\mu \mu_{m_1}(\bar{a}_1, m_1 + m_2) + U_\sigma \sigma_{m_1}(\bar{a}_1, m_1 + m_2) = 0. \tag{16}$$

The interesting question is how country 1's contribution varies with the previous commitment to the adaptation effort. Differentiating (16) with respect to $\bar{a}_1$ and m_1 yields

$$\frac{dm_1}{d\bar{a}_1} = -\frac{f_a^m}{f_m^m}. \tag{17}$$

As $f_m^m < 0$, the reaction depends on the sign of f_a^m, which tells us how the marginal utility of mitigation measures changes when we increase adaptation efforts slightly. Even though one might argue that adaptation and mitigation are no perfect substitutes, it is quite plausible that there is some degree of substitutability, i.e., damages that can be avoided by further mitigation could also be reduced by strengthening adaptation efforts. In this case, we have $f_a^m < 0$. An increase in adaptation in the first stage then decreases the mitigation efforts in the second stage.[12]

As m_1 varies with adaptation efforts, the entire contribution game will be affected by the commitment strategy. We analyze this effect by turning to stage 1 of the game. We maximize the utility $U(\mu(a_1, m_1 + m_2), \sigma(a_1, m_1 + m_2))$ over a_1, which

[11] The other country may simultaneously decide on adaptation measures. For simplicity, we take the adaptation efforts of the other country as exogenously given.

[12] Alternatively, mitigation and adaptation could reinforce each other; then we have complements [$f_a^m > 0$]. Even though there is some debate about complementarity between mitigation and adaptation, this distinction refers to the cross effects on marginal costs rather than on damages; see Ingham, Ma and Ulph (2005) or Ingham, Ma and Ulph (2007).

yields

$$
\begin{aligned}
&U_\mu \cdot \left(\mu_{a_1} + \mu_{m_1} \cdot \frac{\partial m_1}{\partial a_1} - \frac{\partial \alpha}{\partial m} \cdot \frac{\partial m_2}{\partial m_1} \cdot \frac{\partial m_1}{\partial a_1} \cdot \bar{\mu}_1 \right) \\
&+U_\sigma \cdot \left(\sigma_{a_1} + \sigma_{m_1} \cdot \frac{\partial m_1}{\partial a_1} - \frac{\partial \alpha}{\partial m} \cdot \frac{\partial m_2}{\partial m_1} \cdot \frac{\partial m_1}{\partial a_1} \cdot \bar{\sigma}_1 \right) = 0.
\end{aligned} \tag{18}
$$

Using the first-order condition (16), the expression simplifies to

$$
[U_\mu \mu_{a_1} + U_\sigma \sigma_{a_1}] + [-U_\mu \bar{\mu}_1 + U_\sigma \bar{\sigma}_1] \cdot \frac{\partial \alpha}{\partial m} \cdot \frac{\partial m_2}{\partial m_1} \cdot \frac{\partial m_1}{\partial a_1} = 0. \tag{19}
$$

The first term in square brackets describes the marginal utility from additional adaptation efforts neglecting the strategic effects [see equation (12)]. The second term captures the commitment effect of early adaptation. It measures the impact on marginal utility, when adaptation is slightly increased and the mitigation efforts of the other country are adjusted. The first three factors are negative.[13] If adaptation and mitigation are substitutes, the last factor is also negative. Hence, we get the following result:

Proposition 6. If adaptation and mitigation are (imperfect) substitutes in limiting the damages from climate change ($f_a^m < 0$), a country can gain from an early commitment to large adaptation efforts. The commitment strategy induces other countries to increase their mitigation efforts.

The country strategically overinvests in adaptation. The high investments are a credible strategy as they are largely irreversible. In contrast, a commitment to low investments is rarely credible as there is always the opportunity of topping up. The commitment to the adaptation strategy forces the other countries to foster their mitigation efforts. Figure 4 illustrates the effect on the provision of mitigation. The commitment to early adaptation shifts the reaction curve of country 1 inwards. The Nash equilibrium moves from point A to point B. Country 2 has to increase its mitigation efforts. The dashed line describes the mitigation efforts m_1 and m_2 yielding the same global mitigation as in the Nash equilibrium A. In the case depicted, the new Nash equilibrium B is below the dashed line. Hence, the selfish adaptation strategy benefits country 1 but leads to a lower global mitigation effort. However, whenever $\frac{\partial m_2}{\partial m_1} < -1$ holds in equilibrium (i.e. mitigation efforts are more than crowded out), the new equilibrium would be located above the dashed line. Here, the

[13] To be precise, the sign of $\frac{\partial m_2}{\partial m_1}$ depends on the absolute risk aversion and on the convexity of the cost function; see section 2. We neglect the special cases, where extreme values of increasing absolute risk aversion and/or convex costs could make the reaction curve upward-sloping.

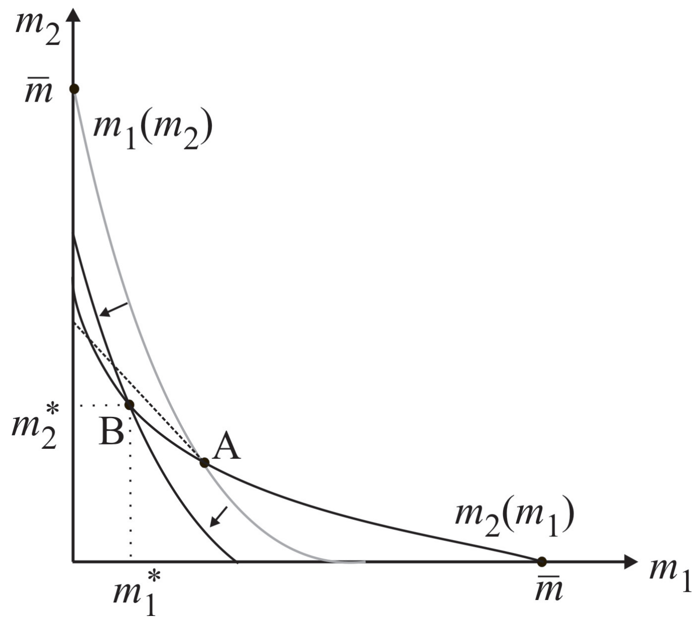

Figure 4: Adaptation as a commitment device

selfish adaptation strategy even helps to generate a lower level of global risks from climate change. Clearly, the other country looses in terms of expected wealth as it has to make larger contributions to the global public good.

4 Conclusion

The proposed model allows to consider explicitly the dimension of uncertainty in climate policy. Uncertainty about the future damages from climate change forces countries to invest in adaptation and mitigation measures as two alternative forms of self-insurance. Our paper shows that the risk dimension even reinforces the crowding-out problem of global mitigation efforts. Even though mitigation may be an efficient measure from a global perspective, unilateral advances in mitigation are ineffective in the absence of a benevolent global government. Unilateral advances work like a wealth transfer to the rest of the world. Making the rest of the world richer also marginally reduces the risk-aversion. The mitigation efforts of the countries are reduced.

We have also shown that adaptation may be a promising strategy. The early investment in adaptation acts as a commitment to low mitigation efforts in the future and thus forces the other countries to pursue a more ambitious mitigation policy.

Admittedly, this paper is only a first step towards the explicit consideration of risk and different risk-taking behavior in models of climate change. There are still many open questions that have to be answered in subsequent research. For instance, we have completely ignored the time dimension. As learning about the damaging effects of climate change will take place over time, countries may benefit from following a waiting strategy as seen in Ingham, Ma and Ulph (2007). Adaptation facilitates such a waiting strategy as it still allows a country to still react to climate change even when it is too late for effective mitigation policies.

A Appendix

A.1 Absolute Risk Aversion

Let S be the slope of the indifference curve $[S \equiv -\frac{U_\sigma}{U_\mu}]$. Absolute risk aversion is decreasing (increasing) if the slope of the indifference curve decreases (increases) with μ_1. Taking the derivative of S with respect to μ_1 yields

$$\frac{\partial S}{\partial \mu_1} = -\frac{U_{\mu\mu}U_\sigma - U_{\mu\sigma}U_\mu}{U_\sigma^2}. \tag{A.20}$$

Hence, absolute risk aversion is

$$\left\{\begin{array}{c}\text{decreasing}\\ \text{constant}\\ \text{increasing}\end{array}\right\} \quad \text{for} \quad U_{\mu\sigma}U_\mu - U_{\mu\mu}U_\sigma \left\{\begin{array}{c}>\\ =\\ <\end{array}\right\} 0. \tag{A.21}$$

A.2 Reaction Curve

The derivatives of equation (3) amount to

$$\begin{aligned} f_m^m = U_{\mu\mu} \cdot (-c_{m_1} - \alpha_m \cdot \bar{\mu})^2 + U_{\mu\sigma} \cdot (-c_{m_1} - \alpha_m \cdot \bar{\mu}) \cdot \alpha_m \cdot \bar{\sigma} \\ + U_\mu \cdot (-c_{m_1 m_1} - \alpha_{mm} \cdot \bar{\mu}) + U_{\sigma\mu} \cdot (-c_{m_1} - \alpha_m \cdot \bar{\mu}) \cdot \alpha_m \cdot \bar{\sigma} \\ + U_{\sigma\sigma} \cdot (\alpha_m \cdot \bar{\sigma})^2 + U_\sigma \cdot \alpha_{mm} \cdot \bar{\sigma} \end{aligned} \tag{A.22}$$

and

$$\begin{aligned} \frac{\partial f^m}{\partial m_2} = U_{\mu\mu} \cdot (-c_{m_1} - \alpha_m \cdot \bar{\mu}) \cdot (-\alpha_m \cdot \bar{\mu}) + U_{\mu\sigma} \cdot (-c_{m_1} - \alpha_m \cdot \bar{\mu}) \cdot \alpha_m \cdot \bar{\sigma} \\ + U_\mu \cdot (-\alpha_{mm} \cdot \bar{\mu}) + U_{\sigma\mu} \cdot (-\alpha_m \cdot \bar{\mu}) \cdot \alpha_m \cdot \bar{\sigma} \\ + U_{\sigma\sigma} \cdot (\alpha_m \cdot \bar{\sigma})^2 + U_\sigma \cdot \alpha_{mm} \cdot \bar{\sigma}. \end{aligned} \tag{A.23}$$

As equation (A.22) and (A.23) have similar structures, we can also write

$$\frac{\partial f^m}{\partial m_2} = f_m^m + U_{\mu\mu} \cdot (-c_{m_1} - \alpha_m \cdot \bar{\mu}) \cdot c_{m_1} + U_{\mu\sigma} \cdot \alpha_m \cdot \bar{\sigma} \cdot c_{m_1} + U_\mu \cdot c_{m_1 m_1}. \tag{A.24}$$

Substituting in (10) leads to equation (11).

A.3 Second-Order Condition

The second-order conditions are

$$f_a^a < 0 \qquad f_m^m < 0 \qquad |D| = f_a^a f_m^m - (f_m^a)^2 > 0. \tag{A.25}$$

We can rewrite the second-order condition $|D| > 0$ as

$$
\begin{aligned}
f^a_a f^m_m \; - \; (f^a_m)^2 &= [A + U_\mu \mu_{aa} + U_\sigma \sigma_{aa}][A + U_\mu \mu_{mm} + U_\sigma \sigma_{mm}] \; - \; [A + U_\mu \mu_{am} + U_\sigma \sigma_{am}]^2 \\
&= A[U_\mu \mu_{mm} + U_\sigma \sigma_{mm}] \; + \; A[U_\mu \mu_{aa} + U_\sigma \sigma_{aa}] \\
&\quad + [U_\mu \mu_{aa} + U_\sigma \sigma_{aa}][U_\mu \mu_{mm} + U_\sigma \sigma_{mm}] \\
&\quad - 2A[U_\mu \mu_{am} + U_\sigma \sigma_{am}] - [U_\mu \mu_{am} + U_\sigma \sigma_{am}]^2 \\
&= A[-U_\mu \bar{\mu} + U_\sigma \bar{\sigma}][\alpha_{mm} + \alpha_{aa} - 2\alpha_{am}] + [-U_\mu \bar{\mu} + U_\sigma \bar{\sigma}]^2[\alpha_{aa}\alpha_{mm} - \alpha^2_{am}]
\end{aligned}
$$

with

$$
A \equiv U_{\mu\mu}\mu_i\mu_j + U_{\mu\sigma}\mu_i\sigma_j + U_{\sigma\mu}\mu_j\sigma_i + U_{\sigma\sigma}\sigma_i\sigma_j \tag{A.26}
$$

and $i, j = \{a, m\}$. The second-order condition is always fulfilled if we have

(A1) $A < 0$

(A2) $\alpha_{ii} - \alpha_{ij} > 0$,

i.e. the cross-derivative $U_{\mu\sigma}$ should not be too strongly positive and an increase in climate measure i reduces the marginal productivity α_i more than an increase in measure j. The latter implies some degree of complementarity between adaptation and mitigation. In the case with perfect substitutability, we have $\alpha_{ij} = 0$.

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