Climate Policy Must Favour Mitigation Over Adaptation

June 15, 2018

Abstract

In climate change policy, adaptation tends to be viewed as being as important as mitigation. In this article we present a simple yet general argument for which mitigation must be preferred to adaptation at the global level. The argument rests on the observation that mitigation is a public good while adaptation is a private one. This implies that the more one teases out the public good nature of mitigation, the lower will be the incentives to invest in the private good adaptation while it increases a policy maker's incentives to invest in the public good mitigation. Conclusively, private adaptation yields a significant loss to global welfare. When taking this result to the data we find that a representative policy maker who does not distinguish between private and public goods would invest in both adaptation and mitigation, just as the previous literature recommends. However, a representative policy maker who properly models mitigation as a public good and adaptation as a private one would optimally only invest in mitigation. We then discuss what this implies for the current state of the art literature and what should be the lesson for future research.
Keywords: mitigation, adaptation, aggregation, public good, private good.
JEL classification: Q58, Q54.

1 Introduction

Adaptation is increasingly seen as an important contributor to climate policy, if not one of the main potential 'solutions' to our climate change problem (IPCC, 2014b). For example, the IPCC (Parry, 2007) notes that "[e]ffective climate policy aimed at reducing the risks of climate change to natural and human systems involves a portfolio of diverse adaptation and mitigation actions (very high confidence)."[1] One, nevertheless, cannot but feel uneasy about this additional policy option as adaptation reduces the incentives to invest in emission reduction (Farnham and Kennedy, 2014) and thus it imposes a negative externality on all others. This leads to more climate change and consequently a greater need to undertake additional climate policy. In the worst case adaptation will simply turn out to be a white elephant. It goes without saying that this feedback cycle can lead to significant increases in global warming, to the extent that adaptation can become very costly or even impossible. As a result, this will give rise to a violation of many of the well-accepted definitions of sustainable development that were developed during the past years, especially strong sustainability (Neumayer, 2003) and approaches relying on capabilities (Sen, 1987). In the light of this the question raised here is as follows: If our climate policy were to be motivated by the first best, should adaptation be part of the policy mix or not? Or, slightly differently, assume a politician who attends the next Conference of Parties meeting comes to you and asks: Having the choice between mitigation and adaptation, how should I lobby all of the world's

[1] This attitude towards adaptation seems to be omnipresent in major international and national governments. For example, the European Union places adaptation highly on its policy agenda in the 2013 EU Strategy on Adaptation; the United Nations Environmental Program developed the National Adaptation Plan which lends support to national governments in their adaptation; and the UNFCCC promises to channel 100 billion USD to developing countries through its Green Climate Fund by 2020.

leaders to split up their money between the two?

One of the reasons for which adaptation has seen increasing attention on the policy agenda is that prominent research suggests that both adaptation and mitigation should play a role in climate policy. This result comes out of a growing literature that studies optimal climate policies in a representative agent framework. The articles that we are aware of and that have treated this question in an analytical approach, in order of publication year, are Lecocq and Shalizi (2007), Yohe and Strzepek (2007), De Zeeuw and Zemel (2012), Bosello et al. (2013), Bréchet et al. (2013), Ingham et al. (2013), Tsur and Withagen (2013), van der Ploeg and de Zeeuw (2013), and Zemel (2015).[2] In this line of literature the discussion tends to circulate around the conditions under which adaptation and mitigation are substitutes or complements, and the optimal mix between adaptation and mitigation. The integrated assessment literature (Hope, 2006; De Bruin et al., 2009; Bosello et al., 2010) has verified these theoretical models empirically and came to the conclusion that adaptation should play a major role in climate policy. While this literature has elicited certain conditions under which, for example, adaptation (or mitigation alike) is optimally neglected (i.e. set to zero) in climate policy, this result tends to stem from either specific functional forms, or depends on the level of economic development of a country.

[2] A review and deeper discussion of these models is available in Agrawala et al. (2011), Bosello et al. (2010), Patt et al. (2010) and Konrad and Thum (2013).

In addition to these studies, there are authors who suggest that mitigation should be viewed as a public good while adaptation is a private one. This literature tends to split the world into several regions and looks more deeply at the inefficiencies that are introduced by this distinction. The earliest contribution is Kane and Shogren (2000), who take the perspective of a country that takes the mitigation effort of other countries as given and then chooses its own adaptation and mitigation strategies. More in line with multiple region models, Mendelsohn (2000) showed that private adaptation would be inefficiently low if joint adaptation would be possible (e.g. in the case of dam construction). A similar result has been shown in Ingham et al. (2013) and Buob and Stephan (2011), who find that adaptation is higher while mitigation is lower in a non-cooperative game compared to a cooperative one. Ebert and Welsch (2012) and Brechet et al. (2014) also study the differences between non-cooperative and cooperative results. Farnham and Kennedy (2014) show that reducing mitigation while increasing adaptation imposes a negative externality on other countries and thus adaptation can be welfare-reducing.

In this article we follow the second strand of literature by splitting the world more realistically into many regions or players and assume that mitigation is a public good while adaptation is a private one.[3] Though this

[3] Here we follow the standard definition in Samuelson (1954) of public and private goods.

distinction has been made in articles that assess climate policy strategies, we will not focus on inefficiencies or particular game structures. Instead, in Section 2 we show that it is the public good character of mitigation that makes a global policy maker to fully favour mitigation over adaptation. The intuition for this is that the more one teases out the public good nature of mitigation the more important will be this public good relative to the private one. Imagine a policy maker uses the standardly used representative agent model that does not distinguish between adaptation as a private good and mitigation as a public one. Then since there is only one agent, a dollar invested in adaptation or mitigation will only benefit this one representative individual. Instead, assume the policy maker models adaptation at the smallest possible unit, namely the individual level (e.g. in the case of air conditioners), while an investment in mitigation benefits all individuals (e.g. climate change). Then he knows that a dollar spent on adaptation helps only one individual, whereas a dollar spent on mitigation helps 7.3 billion people. This is the observation that underlies the results in this article. Intuitively, this should favour the provision of the public good mitigation over the private good adaptation. Hence, private adaptation represents a significant loss to global welfare. In Section 3, based on a numerical exercise calibrated to world data, we show that a policy maker who relies on a welfare function that is disaggregated at least at the country-level would optimally set adaptation equal to zero, while mitigation should be positive. Instead, a policy maker who evaluates welfare at a higher level of aggregation would invest in both adaptation and mitigation. We then argue in Section 4.1 as to what is the 'right' level of disaggregation when evaluating climate policies. Section 5 concludes with further lessons.

2 A simple model

The objective of this section is to understand the implication of teasing out the public good nature of mitigation. We are not claiming that this is the right approach that allows us to consistently go from a disaggregated model to its aggregated version.[4] However, it is the only approach that helps us in understanding when a public good starts to dominate a private simply due to it being public.

We present a simple yet sufficiently general model to answer the question above. Assume there are $n = 1, ..., N$ levels of disaggregation, where $N = 1$ is the representative agent level, and $N = 7.3$ billion is the number of individuals on the planet. Then world income is given by W and average wages by W/N, which can be spend on abatement or mitigation. Let us also assume that for each level of disaggregation all units

[4] I thank Reyer Gerlagh for raising this point.

are the same. Wages net of abatement and mitigation are reduced by multiplicative damages which are a decreasing function of the mitigation effort $M_i \geq 0$ and adaptation effort $A_i \geq 0$, implying that net income is given by $Y_i = \big(1 - D(\sum_1^N M_i, A_i)\big)\big(W/N - A_i - M_i\big)$. Mitigation has a public good character (via e.g. emission reductions that affect CO_2), while adaptation is a private good (e.g. reinforcing one's home against storm damages). For simplicity let's call the different levels of disaggregation 'the agents'. The agents have a concave utility function that depends on net income, $U(Y_i)$, where the sum of mitigation and adaptation efforts are constrained by net wages. We impose the following set of very general assumptions.

Assumption 1 *The utility function* $U : \mathcal{R}_+ \rightarrow \mathcal{R}$ *is an increasing, concave transformation of* Y*.*

Assumption 2 *The damage function takes the form* $D(\sum_1^N M_i, A_i) \in (0, 1)$, $D'_M < 0$, $D''_{MM} > 0$, $D'_A < 0$, $D''_{AA} > 0$, *and* $\lim_{M\rightarrow\infty} D'_M = 0$, $\lim_{A\rightarrow\infty} D'_A = 0$, $D''_{AM} > 0$, *in addition to* $\lim_{M\rightarrow 0} D'_M \geq -\infty$ *and* $\lim_{A\rightarrow 0} D'_A > -\infty$

While the first conditions in Assumption 2 on the shape of the damage function are natural, the last limit condition needs some elaboration. We impose the assumption that $\lim_{A\rightarrow 0} D'_A > -\infty$, meaning that the impact of adaptation, when adaptation is very low, is limited (Moser and Ekstrom, 2010), solely to have a mathematically clear result. This assumption is absolutely not necessary for the central conclusions drawn here, but it does facilitate the subsequent presentation. Still there are some realistic foundations to it. More specifically, it is inspired by the fact that it is not enough to e.g. only replace one tile on the roof with a strong, storm-resistant one, but in order to have a safer house one needs to redo the whole roof. Or, similarly, in order to prevent flooding it is not simply sufficient to use one sandbag, but instead one has to surround one's house with a flood barrier that is high enough. Hence the idea is that adaptation should have a certain threshold good character, or at least be not infinitely productive at the lowest margin. We also confirm that this is a reasonable assumption in our numerical exercise.

We furthermore impose the following technical conditions.

Assumption 3 $W > -\frac{1-D(0,0)}{D'_M(0,0)}$ *and* $W > -\frac{1-D(0,0)}{D'_A(0,0)}$.

These two conditions in Assumption 3 imply that mitigation and adaptation are, at least to some extent, beneficial to curb the impact of climate change and not too expensive. In other words, we assume that there is a role for either mitigation or adaptation in climate policy.

Assume a benevolent policy maker maximizes the sum of the utility functions at the different levels of disaggregation. For example, $N = 1$ is the level of the representative agent that does not distinguish between private and public goods. Instead, for $N = 195$ then adaptation is measured at the country level, while $N = 7.3$ billion is the level for which adaptation is measured at the individual level. Knowing that everyone behaves the same this policy maker[5] maximizes

$$V = NU\Big((1 - D(NM, A))\big(W/N - A - M\big)\Big). \tag{1}$$

Then it is clear that the maximum is achieved when

$$-D'_A(NM, A)\big(W/N - A - M\big) \leq 1 - D(NM, A), \tag{2}$$

$$-D'_M(NM, A)\big(W/N - A - M\big) \leq \frac{1 - D(NM, A)}{N}, \tag{3}$$

where (2) holds with equality if $A > 0$, while (3) holds with equality when $M > 0$. We summarize the first results in the following proposition.

Proposition 1 *Under Assumptions 1 and 2 the maximization problem (1) yields*

1. *a corner solution in both adaptation $A = 0$ and mitigation $M = 0$ if*

$$\frac{W}{N} < -\frac{1 - D(0,0)}{D'_A(0,0)}, \tag{4}$$

[5] As Geir Asheim suggested, there is another way in which the model can be set up. We could instead have written $V = NU\Big((1 - D(M, A/N))\big(W - A/N - M/N\big)\Big)$, which implies that as N increases we make abatement less public. The intuition is similar and the results precisely the same. Both approaches are perfectly defensible and thus it is only a matter of taste which one to use.

and

$$W < -\frac{1 - D(0,0)}{D'_M(0,0)}. \tag{5}$$

2. *a corner solution in adaptation $A = 0$ alone if, for an optimum interior M^*,*

$$M^* > \frac{W}{N} + \frac{1 - D(NM^*,0)}{D'_A(NM^*,0)}, \tag{6}$$

and

$$M^* = \frac{1}{N}\left(W + \frac{1 - D(NM^*,0)}{D'_M(NM^*,0)}\right) \tag{7}$$

which jointly requires

$$D'_M(NM,0)N < D'_A(NM,0), \tag{8}$$

3. *and a corner solution in mitigation $M = 0$ alone if, for an optimum interior A^*,*

$$A^* > \frac{1}{N}\left(W + \frac{1 - D(0,A^*)}{D'_M(0,A^*)}\right), \tag{9}$$

and

$$A^* = \frac{W}{N} + \frac{1 - D(0,A^*)}{D'_A(0,A^*)} \tag{10}$$

which jointly requires

$$ND'_M(0,A^*) > D'_A(0,A^*). \tag{11}$$

4. an interior solution in mitigation $M > 0$ and adaptation $A > 0$ if

$$W/N - A^* - M^* = -\frac{1 - D(NM^*, A^*)}{D'_A(NM^*, A^*)} = -\frac{1 - D(NM^*, A^*)}{ND'_M(NM^*, A^*)}, \quad (12)$$

which requires

$$ND'_M(NM^*, A^*) = D'_A(NM^*, A^*). \quad (13)$$

■

Proof 1 *Follows directly from perturbing equations* (2) *and* (3) *and applying the Kuhn-Tucker conditions.* ■

We now show that the public good character of mitigation and the private good character of adaptation play a crucial role for the optimal mix between adaptation and mitigation. In particular, we shall not, as is usual, focus on the demand side (properties of non-excludable and non-rival) of public goods, but instead on the supply side. As suggested above, the focus will be on the first-best, the social optimum, and thus we also do not look at the free-rider problem or the externality-induced inefficiencies of over/under-provision which are generally associated with public goods.[6] Instead, we look at the supply side in order to more clearly tease out the public good

[6]These focuses basically come out of the literature on group size and public goods starting with Olson (1965) and Chamberlin (1974).

character of mitigation by making it more 'public' relative to the private good adaptation.

Imagine you are a policy maker and you maximize wealth subject to adaptation and mitigation for the world as a whole ($N = 1$), ignoring that there are many agents out there that jointly benefit from marginal expenditures on mitigation. This, basically, is what is being done in the representative agents models up to now. In this case, the public good mitigation would be indistinguishable from a private good. In contrast, assume you maximize over the major regions of the world (e.g. PAGE2002 assumes $N = 8$ and RICE-2010 model assumes $N = 12$). Then the fact that the world income is now split over 12 regions matters for the optimal choices. Take this now to the extreme and assume that 7.3 billion individuals are considered by the policy maker. Average income will be very low in this case, and consequently there will only be a limited budget available for private adaptation, while the potential sum for the public good mitigation can be very large. Intuitively, this should favour the provision of the public good mitigation over the private good adaptation.

Let us see whether this intuition applies to the optimal mix between the public good mitigation and the private good adaptation. Assume we are in *case 2*, which corresponds to parameter conditions that yield an interior solution in mitigation but a corner in adaptation. Then from the optimal condition for M^*, equation (7), we get

$$\frac{dM^*}{dN} = -\frac{M^*}{N} = -\frac{1}{N^2}\left(W + \frac{1-D}{D'_M}\right) < 0. \tag{14}$$

The left-hand side of inequality (6) decreases in N. In contrast, the right-hand side of the inequality changes with N according to

$$\frac{d\left(\frac{W}{N} + \frac{1-D(NM^*,0)}{D'_A(NM^*,0)}\right)}{dN} = -\frac{W}{N^2}.$$

Hence, the left-hand side of the inequality reduces more slowly than the right-hand side if N increases. As a result, if case 2 applies for a given N, then it will still hold for increasing N. This is also confirmed for the joint condition (8) which, if it holds for a given N, also holds for a larger N.

Assume now we are in *case 3*, thus $M = 0$ and $A > 0$ is optimal. Then from the optimal A^* derived in equation (10) we obtain

$$\frac{dA}{dN} = -\frac{W}{N^2(2 + \frac{1-D(0,A)}{D'_A(0,A)^2 D''_{AA}})} < 0. \tag{15}$$

In addition, from equation (10) we can find that the optimal $A^* = 0$ for $N \geq -\frac{D'_A(0,0)W}{(1-D(0,0))}$.

We, therefore, find that for increasing N it becomes increasingly unlikely that *case 3* holds. The condition for this is summarized in the following proposition.

Proposition 2 *$A^* = 0$ if, for any optimal M, $N \geq \frac{-D'_A(NM,0)W}{1-D(NM,0)}$.*■

Proof 2 *Based on equation (10), we re-write the condition from Proposition 2 as*

$$\frac{W}{N} = A^* - \frac{1 - D(0, A^*)}{D'_A(0, A^*)}.$$

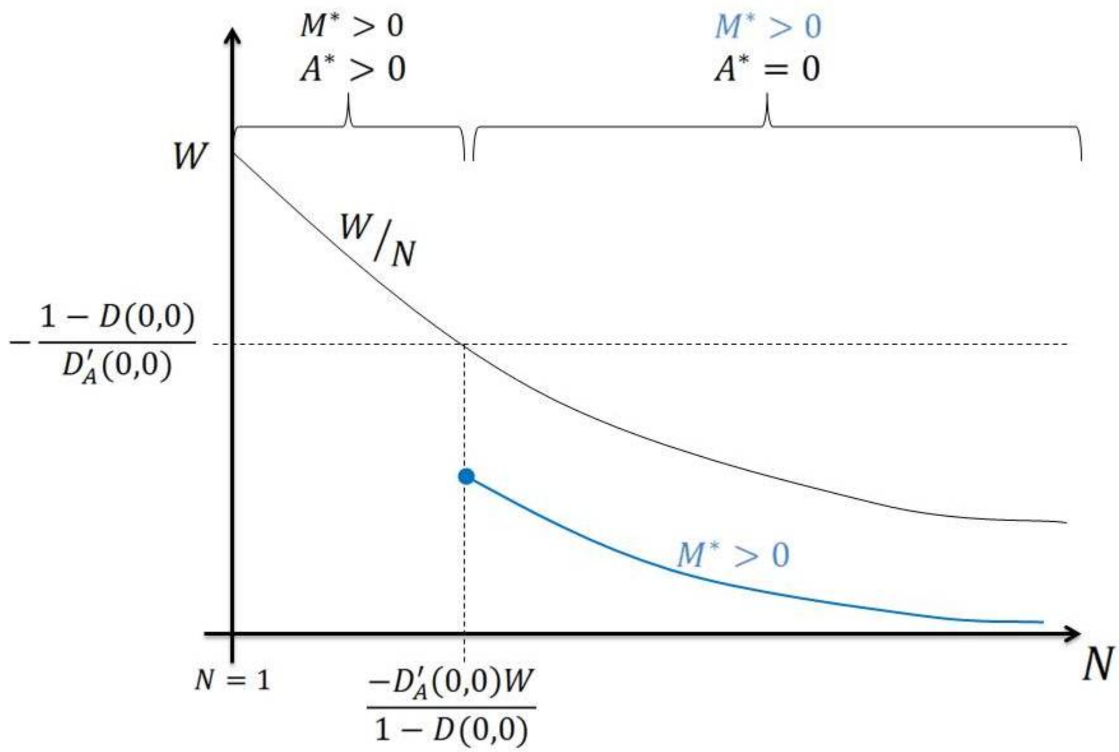
As $A^* - \frac{1-D(0,A^*)}{D'_A(0,A^*)}$ is an increasing function of A and $-\frac{1-D(0,0)}{D'_A(0,0)} > 0$, then this condition will not be satisfied if $W/N < -\frac{1-D(0,0)}{D'_A(0,0)}$. Also,

$$\frac{d\left(\frac{1-D(0,0)}{D'_A(0,0)}\right)}{d(NM)} = -\left(\frac{D''_{AM}W}{1-D} + \frac{D'_A D'_M W}{1-D)^2}\right) < 0.$$

Re-writing yields the condition in the proposition above. ■

Figure 2 shows the condition under which the maximization problem yields a corner solution in adaptation and an interior solution in mitigation given that Assumption 3 holds.

Hence, for a sufficiently disaggregated welfare function we find that mitigation should be favoured over adaptation. Furthermore, we conjecture that this result will continue to hold in the case of multiple periods and asymmetric agents, and it will be strengthened if we include uncertainty, the risk of climate catastrophes, and e.g. the inability to migrate to safer



regions. The result above also suggests that both representative agent models, such as Kane and Shogren (2000), Lecocq and Shalizi (2007), Yohe and Strzepek (2007), De Zeeuw and Zemel (2012), Bosello et al. (2013), Bréchet et al. (2013), Ingham et al. (2013), Tsur and Withagen (2013), van der Ploeg and de Zeeuw (2013), Zemel (2015), or integrated assessment models based on a global or (smaller) regional split-up of the world, such as Nordhaus (1993), Hope (2006), De Bruin et al. (2009) or Bosello et al. (2010), will underestimate the optimal mitigation action and overestimate the optimal adaptation effort since they do not, or only minimally, take the public versus private good setting into account.

3 Empirical considerations

In this section we shall pretend that the mitigation option is evaluated at different levels of public good. For example, a policy maker who evaluates mitigation at the national level would not consider how mitigation affects each individual, but this policy maker would analyze how it affects the country as a whole. This, coincidentally, is also the only way in which we can empirically show how the public good nature of mitigation starts to dominate the private good adaptation as a policy option from the global welfare perspective. We will now investigate inhowfar these theoretical results carry forward to empirically relevant settings. To do so we build upon Golosov et al. (2014) and define the damage function as follows.

Assumption 4 *The damage function takes the form* $D(\sum_1^N M_i, A_i) = 1 - \exp\Big(-\gamma(A_i)\big(S(W, \sum_i M_i) - \bar{S}\big)\Big)$, *where* $\gamma(A_i)$ *denotes the damage elasticity, while* $S(W, \sum_i M_i) - \bar{S}$ *is the difference between the current atmospheric carbon level and the pre-industrial one.*

Hassler et al. (forthcoming) show that this damage function is a useful approximation relative to Nordhaus' (Nordhaus, 2007) damage function. Golosov et al. (2014) assume the damage elasticity parameter to be given exogenously, while we endogenize it through adaptation expenditure $\gamma(A_i)$.

An obvious question is as to how adaptation affects the damage elasticity parameter and how mitigation precisely affects carbon emissions. Clearly, there is an inherent lack of acceptable estimates concerning the way adaptation and mitigation help to reduce damages from climate change. Based on a survey in Tol et al. (1998), De Bruin et al. (2009) estimate that the costs of adaptation increase exponentially with the damages avoided. Similar, more recent Integrated Assessment Models (Agrawala et al., 2011) empirically estimate functional forms equivalent to ours. The functional form that we use henceforth and that approximates this is given in Assumption 5 below.

Similarly, it is known that mitigation at low carbon emissions is reasonable cheap, while trying to mitigate all emissions is extremely costly. As mitigation may take many forms of emission reductions, such as investments in renewable energies like wind or solar, reforestation projects or investments in less carbon-intensive products, we take the empirical form given in Assumption 5.

Assumption 5 *The damage elasticity is given by* $\gamma(A_i) = \frac{\gamma}{1+A_i}$. *The atmospheric carbon level is given by* $S(W, \sum_i M_i) = \phi \frac{W}{1+\sum_i M_i} + 848$.

Thus, both the damage elasticity and the atmospheric carbon level are convex functions of their arguments. We also take it that mitigation will not reduce the level of atmospheric carbon below the pre-industrial level, which is not a necessary but convenient assumption. In the definition of $S(W, \sum_i M_i)$ the value 848 is the current (2015) level of atmospheric carbon measured in Gigatons Carbon (GtC).

One may argue that higher levels of adaptation lead to lower net income levels and thus less carbon is emitted. However, there are many cases where adaptation actually increases emissions, e.g. via increased use of air conditioning in order to compensate for rising temperatures. Similarly, improving one's housing structure requires the production of more cement, of stronger tiles, of better isolated windows, all of which adds to carbon emissions. We thus take the most reasonable case and assume that producing a unit of adaptation expenditure has the same impact on the atmospheric carbon stock as a unit of income.

In the following we will take this static model and assume that a benevolent policy maker looks ahead until 2050 when deciding upon the optimal adaptation and mitigation policy. Instead of adding utilities over the different periods we take average IPCC climate, as well as average World Bank population and income growth scenarios. We then sum up over the income from 2015 to 2050, and allow the policy maker to choose his climate policy statically. By doing so we will only obtain the average per period adaptation and mitigation expenditure, and ignore potential effects that are due to the curvature of the utility function or discounting. While this may somewhat affect the level of the optimal choices, this should not impact the qualitative results. Furthermore quantitative differences should be small for the low discount rates that are currently used in climate policy, and also for utility functions with little curvature (e.g. the DICE model of Nordhaus uses a logarithmic utility).

It is now required to calibrate the parameters γ and ϕ. The parameter γ is the damage elasticity. We use the RCP8.5 scenario of the IPCC, which is an unmitigated scenario that predicts a level of atmospheric carbon of 1,378 GtC in 2050. According to Figure SPM.5 from the 2014 IPCC Synthesis Report (IPCC, 2014b), the associated warming will be around $2.5°C$. Damage estimates for this level of warming vary to some degree. According to the IPCC (Field et al., 2014) and the Stern review (Stern, 2007), losses from a $2°C$ temperature increase amount to between 0.2 to 2% of income, with losses being more likely at the higher end of the spectrum. Thus, a $2.5°C$ warming is likely to be closer to losses of 2%, if not higher. In a recent study, Burke et al. (2015) estimate the aggregated world damages for $2.5°C$ warming to be 10% of world GDP. Due to a lack of better estimates we place slightly more weight on the estimates from the IPCC, and take it that a $2°C$ warming induces damages of 4% of world GDP. The pre-industrial level of atmospheric carbon was around 590 GtC (in 1750). Assuming that this level of carbon was such that mankind had fully adapted to the climate conditions, then using this information to estimate γ we find that the unabated and unmitigated baseline scenario of 1,378 GtC in 2050 yields $0.96 = 1 - \exp\big(-\gamma(1,378 - 590)\big)$. Thus, this gives a value of $\gamma = 5.18 \times 10^{-5}$. Golosov et al. (2014) obtain a very similar damage elasticity of $\gamma = 5.3 \times 10^{-5}$. Furthermore, our damage estimates conform very closely to those by Nordhaus (2007), whose estimates would yield a damage of 3.5% at 1,378 GtC. However, our damage estimates are more linear in temperature than Nordhaus (2007) and overestimate the damages for low carbon concentrations but underestimate them for high levels of carbon concentrations. Nevertheless, a more linear relationship makes our model more in line with the recent empirical results of Burke et al. (2015).

The parameter ϕ is obtained as follows. The Gross World Product (in PPP, 2011 dollars) was 107.5 trillion US \$. Annual world carbon emissions are currently 10.35 GtC. Thus, the propensity to emit from world income is $\phi = 10.35/107.5$. Since, according to the IPCC (2014a), roughly 50% of the emitted carbon leaves the atmosphere during the course of a couple of years, we multiply this by 0.8, which takes into account that more carbon is emitted closer to 2050 implying that less could have left the atmosphere. We set the expected world growth rate until 2050 to 3%, which is slightly lower than the recent 3.4% noted in the IMF's World Economic Outlook but includes the potential for growth convergence. Given that the pre-industrial carbon level was 590 GtC in 1790 and that the current level of carbon in the atmosphere is 848 GtC, then this yields[7] a maximum carbon level of 1,372 GtC in 2050, which corresponds very closely to the 1,378 GtC obtained via the RCP8.5 scenario of the IPCC. Thus, it seems this simple model approximates the more complicated integrated assessment models rather well.

We then numerically maximize the welfare function under different assumptions on how the policy maker aggregates the social welfare function: We assume (s)he may maximize the welfare function treating the world as a) a single entity (the world); b) split up in 12 regions (e.g. as in the RICE model); c) split up in its 193 countries; d) split up into 8 billion people[8]. The results are depicted in Table 1. We observe that if the policy maker

Table 1: Numerical results

Split-up	**Adaptation**	**Mitigation**	**Total mitigation**
World	10.71	2.967	2.967
RICE regions (12)	2.085	0.56	6.715
Countries (193)	0	0.065	12.484
Individuals (8 bill.)	0	1.56×10^{-9}	12.484

takes a country-level perspective, then the optimal adaptation expenditure tends to zero. In fact, given the calibration above, adaptation will be equal

[7] The calculation is as follows: $848GtC + 0.8 \times 10.35GtC/107.5\$ \times \sum_{t=0}^{3} 5(1+0.03)^t 107.5\$ = 1,372$ GtC.

[8] There are currently 7.3 billion people on this planet. According to the World Bank, the world population may (intermediate scenario) approach 8.6 billion by 2050. An average over the period 2015-2050 is roughly 8 billion.

to zero for a social welfare function that consists of a disaggregation level of 110 or more agents/regions. The results presented here confirm that it is important to fully take the public good nature of mitigation into account when deciding upon the optimal mix with the private good adaptation.

4 Implications for the literature

The result above is, obviously, not a fully fledged integrated assessment model result but only a back of the envelope calculation. But it should serve as a reminder that globally aggregated models, or those that do not fully take into account the public versus private good nature of mitigation and adaptation, will necessarily lead to biased results. For example, the AD-DICE model (De Bruin et al., 2009) models both mitigation and adaptation at the global level and comes to the conclusion that both should be optimally positive. We argue that this is a direct result of ignoring the public good nature of mitigation. Similarly, while the PAGE2002 model (Hope, 2006) does incorporate several world regions and studies the role of adaptation and mitigation, it evaluates mitigation only at the level of the eight world regions. As we show in the numerical example above, this is not enough to fully tease out the public good character of mitigation.

Lecocq and Shalizi (2007), like us, also model a global planner that optimizes between a private good adaptation and the public good mitigation. They do, however, not investigate what the implication of the public good character of mitigation really means and stop at concluding that there is an interior trade off between mitigation and adaptation. As we have shown above, it is generally not the case that a global planner would invest in the private good adaptation since the public good mitigation completely dominates it in terms of global welfare. Lecocq and Shalizi (2007) distinguish between proactive and reactive adaptation. An example of proactive adaptation is the construction of a dam and represents investments in adaptation that may also accumulate over time, while reactive adaptation is expenditure undertaken at the time a disaster strikes (e.g. evacuation). It is certainly true that there are important trade-offs between reactive and proactive adaptation. However, from the modeling above it should be clear that this further distinction[9] does not impact our main take away point, namely that the public good character of mitigation tends to dominate any kind of adaptation measures from a global welfare point of view.

De Zeeuw and Zemel (2012) develop a representative agent model where they study the trade off between adaptation and mitigation, where mitiga-

[9]This is in line with Ingham et al. (2013), who show that proactive and reactive abatement play very similar roles from a social planner's perspective, and also extending the model to an infinite horizon case will lead to similar results.

tion takes the form of emissions foregone, when regime shifts can lead to abrupt changes in the damage function (e.g. a breakdown of the thermohaline circulation). However, they do not distinguish between adaptation being a private good and mitigation a public one, and thus subsequently find that both should be undertaken at the global optimum. If one were to re-write their model allowing for mitigation to be a public good[10], then this significantly reduces the optimal steady state pollution level ($\hat{P}$). In fact, for N large enough this level will be close to zero, implying that no emissions should be undertaken. As a result, the post-event value of the welfare function will be zero and no adaptation would be optimal (see their equation 7.1). Strictly speaking, this result is clearly a direct implication of assuming that mitigation action is equivalent to not emitting carbon. Nevertheless, we hypothesize (and in our discussion of the next paper we show this) that even if one were to explicitly model mitigation, then our result would continue to hold.

Bréchet et al. (2013) provide a Ramsey-type model where mitigation is modeled as a flow technology of emission reductions while adaptation is a stock variable. Higher investments in the stock of adaptation then reduce the impact of climate damages which is measured in utility terms.

[10]Using the authors' notation and denoting by N the number of agents we re-write their pollution equation (2.1) as $\dot{P} = NE - \alpha P$, and their instantaneous utility as $N(\beta E - E^2/2 - \gamma_2 P_2^2)$. Their model corresponds to the case of $N = 1$.

If we re-write their model in order to distinguish between mitigation as a public good and adaptation as a private one[11] and solve their system, then we find that the marginal utility of consumption should be larger or equal to the marginal value of adaptation stock per agent squared. Thus, this condition will only be satisfied in societies which are unrealistically rich and have unreasonably high levels of pollution at the same time. Using their parameter configuration, we find that per capita consumption must be at least 15.3 million USD to make investments in the private good adaptation worthwhile. These are clearly only back of the envelope calculations, but they do give an idea of the order of magnitude. Similarly to Bréchet et al. (2013), the two articles Zemel (2015) and Tsur and Zemel (2016) also compare the optimal mitigation and adaptation actions when adaptation is a stock variable, the main difference being that the later two articles introduce uncertainty. It should be clear that our arguments from above also extend to their approach.

Ingham et al. (2013) investigate under which conditions mitigation and adaptation would be complements. If one were to be able to extract conditions under which mitigation and adaptation are complements, then this could imply that an interior solution in adaptation may be optimal simply

[11] Using their notation this would yield an instantaneous utility function of $u(C, P, D) = N(\ln(C(t)/N) - \eta(D(t))\frac{P(t)^{1+\mu}}{1+\mu})$ and a pollution constraint of $\dot{D}(t) = I_D/N - \delta D$, where I_D/N implies that investments in adaptation stock are equally split over all individuals N.

because positive mitigation is optimal. Ingham et al. (2013) argue that both could be complements if the costs of adaptation depend on the amount of mitigation undertaken. They argue that e.g. adaptation is cheaper and easier if the speed of climate change is lower. If we adjust their model to the case of mitigation being a public good and adaptation a private one[12] we find that adaptation expenditure will be close to zero.[13] Thus, even if one allows mitigation to have an impact on the costs of adaptation, then we would see relevant levels of adaptation only if this impact is unreasonably large.

Buob and Stephan (2011) build upon Ingham et al. (2013) by introducing income differences and study more fully the non-cooperative versus the cooperative outcome. They have a result similar to ours in that they investigate the impact of changing the number of regions. However, when they change the number of regions they do not keep world income constant but instead multiply each region's income by the number of regions. Thus they introduce a scale effect. This is no problem if one thinks of several regions that potentially interact on public bad. However, it certainly implies that it is difficult to evaluate what is meant by the social optimum. Thus, re-

[12]The easiest way to do this is to divide their adaptation expenditure in the damage function by N.

[13]The reason for it not being zero is because they assume limit conditions that always lead to an interior solution.

writing their model to make it more in line with a global model[14], we find that for sufficiently large N, that means for evaluating mitigation impacts at e.g. the individual level, that adaptation expenditure is close to zero and the region where only adaptation is optimal (c.f. their Figure 3) is pushed upwards in proportion to the number of agents. Thus, for sufficiently large N the region where adaptation is positive requires an unreasonably high level of environmental quality.

Our main result obviously only holds as long as there is a viable trade-off between mitigation and adaptation. So some alert readers would be immediately inclined to forward either of two points. One would be that there are many cases where climate change is already impacting local populations now and hence adaptation is the only viable solution. The other point would be that there is an approximately 80 year delay from current mitigation actions to their impact on CO2 concentrations due to delays in the carbon cycle (Rezai and van der Ploeg, 2015), which would imply that mitigation actions only impact the future while adaptation measures have an impact now already. Clearly, in the first case there is no trade-off between adaptation and mitigation and hence adaptation is potentially a necessary policy but only insofar as there is no direct trade-off between the two. With respect to the delay from mitigation impacts due to the carbon cycle it is

[14]This we do by simply re-writing their per capita income as $y = Y/N$, where Y is global income and N are the number of agents. This gets rid of the scale effect in income when changing N.

clear that there are two options. One, the delay is such that impacts are unavoidable, in which case adaptation will be likely to be a viable policy. Nevertheless, even in this case it is clear that for all avoidable climate damages we would fully prefer mitigation to adaptation. Two, mitigation could take the form of carbon capture and storage which directly reduces carbon in the atmosphere and thus does not require us to wait for a natural carbon uptake. The result above suggests that even if carbon capture and storage is a more expensive technology than adaptation, it would need to be more expensive on the order of several magnitudes before adaptation starts to be a viable policy option from the global welfare perspective.

One recurring question is whether the type of adaptation matters.[15] In this respect, Mendelsohn (2000) analyzes the role of joint adaptation, i.e. the case where one individual's adaptation expenditure has also an impact on another individual's adaptation expenditure. From a modeling perspective this of course blurs the distinction between the purely public good mitigation and the private good adaptation. It is true that some adaptation expenditures benefit a whole country (e.g. building dams in Netherlands). In this case one would have a reasonable argument that some types of large adaptation expenditures have a somewhat public good character. So these

[15] As noted in Barrett (2008) and Ebert and Welsch (2011), one can somewhat circumvent the problem of different types of adaptation, i.e. that they do not have an aggregate physical metric, by looking at adaptation expenditure.

cases would then certainly require a deeper analysis of the mitigation and adaptation trade-offs for this particular case. Nevertheless, if we take our numerical results above at face value, then we have shown that already at the country level it is not optimal to invest in even this type of adaptation expenditure from a global welfare point of view. This suggests that only very few large scale adaptation projects would pass this cost benefit test.

A point generally forwarded (De Zeeuw and Zemel, 2012) is that a country would view the option of adaptation to be especially important if it perceives global climate action to be too limited. This is a non-cooperative argument which we did not delve into since we took the perspective of a global planner who wants to achieve the first best, the global optimum. However, in these regional models (Ingham et al., 2013; Buob and Stephan, 2011; Ebert and Welsch, 2012; Brechet et al., 2014; Farnham and Kennedy, 2014) the recurring argument is that, in contrast to the cooperative case, the non-cooperative equilibrium leads to higher adaptation expenditures and lower mitigation. This is entirely in line with the results of the public versus private good literature (Samuelson, 1954). But a question that generally remains open is how best we could induce the cooperative solution in a non-cooperative setting. Clearly, the arguments in this article suggest that policies must be undertaken to move incentives away from adaptation towards mitigation. For example, global climate treaties provide certainly a key for bringing the non-cooperative solution in line with the cooperative one.

4.1 What is the 'right' N to consider?

It is not entirely clear as to what is the 'right' level at which the welfare function should be evaluated. One important question, therefore, is at which level decisions are taken. Clearly, aggregation helps us to simplify exposition and it also aids us in the understanding of results, it helps us in the modelling and very often it is easier to predict the evolution of the whole than the evolution of its parts. Furthermore, data availability at the individual level is scarce and incomplete. Consequently, higher levels of aggregation tend to be preferred, which also explains the lack of country-level integrated assessment models. However, ever since COP20, and especially in the light of COP21, a global unified regulatory scheme seems far from achievable, and Nationally Appropriate Mitigation Actions re-introduce the country-level perspective back into climate policy making. This thus implies that a policy maker should set N at least at the country-level.

At the same time, most adaptation efforts are undertaken at the household (e.g. house protection against storms) or city (e.g. dam construction) level. For example, farmers protect their soils from desertification by building appropriate water reservoirs. Families invest heavily into fortifying their houses against storm damage. Migrants pay large sums of money to migrate to places that are less susceptible to climate change. These actions tend to see very little governmental support but they nevertheless make the brunt of adaptation efforts. Clearly, this is also unlikely to change in the future. As a result, a policy maker should optimally choose adaptation efforts at the household level. This thus implies that N should be considered to be sufficiently large for the result above to hold for most functional forms of damages.

What one should take away is that optimal climate policy should thus be at least taken with the country-level perspective in mind. In this case the numerical results have shown that adaptation should be set equal to zero and mitigation should be set at a positive level. Again, this is a direct implication of the fact that, while adaptation is a private good, mitigation is a public good and thus small contributions of everyone can have significant impacts at the large. If everyone were to act unilaterally and spend money on individual adaptation then a policy maker would evaluate this as a loss of welfare.

5 Conclusion

If we take the view of a benevolent world policy maker, then the result presented in this paper suggests that, considering a sufficiently disaggregated welfare function (e.g. at the country level), the optimal adaptation effort will be zero, while mitigation effort should be positive. Conclusively, from a global perspective, the public good character of mitigation, by and large, indeed should favour mitigation action over the private good adaptation. From a global perspective, private adaptation thus represents a significant loss of welfare. We augment the known models in the literature in order to be able to study the impact of considering mitigation as a public good while adaptation is a private one and conclude that our result is fully robust.

Based on a numerical exercise calibrated to real-world data we show that a policy maker who evaluates social welfare at the country-level (or higher levels of disaggregation) would not invest in adaptation, but instead would fully focus on mitigation. Furthermore, if adaptation is similar to a threshold good (i.e. take the case of a dam), then this strengthens the point raised in this article. Additional factors that strengthen the above result include uncertainty, the risk of climate catastrophes, the inability to migrate to safer regions, or the inability of the agricultural sector to adapt to certain climatic changes.

The results presented here complement those from the Aggregation Dilemma (Schumacher, 2014), which states that the social cost of carbon increases the more disaggregated the welfare function is since aggregation averages (important) differences away. Thus, if we take aggregation serious, then not only will we not underestimate the social cost of carbon, but we will also optimally neglect adaptation as a viable policy option.[16]

Of course we all know that the world is not ruled by a benevolent planner. Does this imply this result has no meaning? Certainly not, since it simply states that, if we want to achieve the absolute optimum, then we should focus our maximum efforts on mitigation. It is thus a negative result on the position that adaptation necessarily has to play a role in our climate policy mix. It means that if our world leaders are unable to cooperate to a sufficient degree and we cannot achieve the best outcome for everyone, only then may adaptation play a role. However, accepting adaptation as part of our climate policy mix then also entails that we accept climate change and its consequences for our future generations; that we accept our failure to coherently establish international cooperation in order to reduce carbon

[16] Additional points against adaptation are significant biophysical, financial and social constraints that make adaptation a particularly weak policy option. Biophysical constraints tend to be related to natural thresholds that, if once crossed (e.g. desertification), seriously inhibit both nature's as well as mankind's ability to adapt. Financial constraints arise if, for example, poor agricultural households cannot afford to buy the seeds that new climatic conditions require, or to insure themselves sufficiently against greater climate variability; or those needing to migrate have not sufficient funds to do so. Social limits to adaptation require us to know whether we really want to live with three meter high flood barriers around the house; or whether we believe that societies can really easily cope with large-scale climate migrants especially if there are strong cultural differences.

emissions; and that we accept to 'agree' on a global policy that is far from the optimal one. Allowing a large role for adaptation simply means we failed in following the simple Kindergarten Rule of Sustainable Development.

Thus, the point raised here suggests that policy makers should get their priorities straight: It is simply not true that "[e]ffective climate policy aimed at reducing the risks of climate change to natural and human systems *involves a portfolio of diverse adaptation and mitigation actions*." (Parry, 2007) Instead, considering the result presented here, the IPCC should write that "[e]ffective climate policy aimed at reducing the risks of climate change to natural and human systems *must primarily consist of mitigation actions*." This important change in rhetoric, namely that adaptation is a last resort and only a testimony of mankind's inability to cooperate, would also make room for more stringent views on adaptation, for example that adaptation is only acceptable for countries if this does not negatively impact their emission reduction efforts.

References

Agrawala, Shardul, Francesco Bosello, Carlo Carraro, Enrica De Cian, Elisa Lanzi et al., "Adapting to climate change: costs, benefits, and modelling approaches," *International Review of Environmental and Resource Economics*, 2011, *5* (3), 245–284.

Barrett, Scott, "Dikes vs. windmills: climate treatise and adaptation," *Johns Hopkins University, School of Advanced International Studies*, 2008.

Bosello, Francesco, Carlo Carraro, and Enrica De Cian, "Climate policy and the optimal balance between mitigation, adaptation and unavoided damage," *Climate Change Economics*, 2010, *1* (02), 71–92.

_ , _ , and _ , "Adaptation can help mitigation: an integrated approach to post-2012 climate policy," *Environment and Development Economics*, 2013, *18* (03), 270–290.

Bréchet, Thierry, Natali Hritonenko, and Yuri Yatsenko, "Adaptation and mitigation in long-term climate policy," *Environmental and Resource Economics*, 2013, *55* (2), 217–243.

Brechet, Thierry, Natali Hritonenko, Yuri Yatsenko et al., "Domestic environmental policy and international cooperation for global commons," Technical Report, Université catholique de Louvain, Center for Operations Research and Econometrics (CORE) 2014.

Bruin, Kelly C De, Rob B Dellink, and Richard SJ Tol, "AD-DICE: an implementation of adaptation in the DICE model," *Climatic Change*, 2009, *95* (1-2), 63–81.

Buob, Seraina and Gunter Stephan, "To mitigate or to adapt: How to confront global climate change," *European Journal of Political Economy*, 2011, *27* (1), 1–16.

Burke, Marshall, Solomon M Hsiang, and Edward Miguel, "Global non-linear effect of temperature on economic production," *Nature*, 2015.

Chamberlin, John, "Provision of collective goods as a function of group size," *American Political Science Review*, 1974, *68* (02), 707–716.

Ebert, Udo and Heinz Welsch, "Optimal response functions in global pollution problems can be upward-sloping: accounting for adaptation," *Environmental Economics and Policy Studies*, 2011, *13* (2), 129–138.

_ **and** _ , "Adaptation and mitigation in global pollution problems: economic impacts of productivity, sensitivity, and adaptive capacity," *Environmental and Resource Economics*, 2012, *52* (1), 49–64.

Farnham, Martin and Peter Kennedy, "Adapting to Climate Change: Equilibrium Welfare Implications for Large and Small Economies," *Environmental and Resource Economics*, 2014, pp. 1–19.

Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.), *Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.

Golosov, Mikhail, John Hassler, Per Krusell, and Aleh Tsyvinski, "Optimal taxes on fossil fuel in general equilibrium," *Econometrica*, 2014, *82* (1), 41–88.

Hassler, John, Per Krusell, and Jonas Nycander, "Climate policy," *Economic Policy*, forthcoming.

Hope, Chris, "The marginal impact of CO2 from PAGE2002: An integrated assessment model incorporating the IPCC\'s five reasons for concern," *Integrated Assessment Journal*, 2006, *6* (1), 19–56.

Ingham, Alan, Jie Ma, and Alistair M Ulph, "Can adaptation and mitigation be complements?," *Climatic change*, 2013, *120* (1-2), 39–53.

IPCC, *Climate change 2013: The physical science basis, [Core writing team, Stocker, Thomas and Qin, Dahe and Plattner, Gian-Kasper and Tignor, M and Allen, Simon K and Boschung, Judith and Nauels, Alexander and Xia, Yu and Bex, Vincent and Midgley, Pauline M (eds.)]*, Cambridge University Press Cambridge, UK, and New York, 2014.

_ , *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]*, IPCC, Geneva, Switzerland, 2014.

Kane, Sally and Jason F Shogren, "Linking adaptation and mitigation in climate change policy," *Climatic Change*, 2000, *45* (1), 75–102.

Konrad, Kai A and Marcel Thum, "The role of economic policy in climate change adaptation," *CESifo Economic Studies*, 2013, p. ift003.

Lecocq, Franck and Zmarak Shalizi, "Balancing expenditures on mitigation of and adaptation to climate change: an exploration of issues relevant to developing countries," *World Bank Policy Research Working Paper*, 2007, (4299).

Mendelsohn, Robert, "Efficient adaptation to climate change," *Climatic Change*, 2000, *45* (3-4), 583–600.

Moser, Susanne C and Julia A Ekstrom, "A framework to diagnose barriers to climate change adaptation," *Proceedings of the National Academy of Sciences*, 2010, *107* (51), 22026–22031.

Neumayer, Eric, *Weak versus strong sustainability: exploring the limits of two opposing paradigms*, Edward Elgar Publishing, 2003.

Nordhaus, William D, "Optimal greenhouse-gas reductions and tax policy in the" DICE" model," *The American Economic Review*, 1993, *83* (2), 313–317.

_ , "To tax or not to tax: Alternative approaches to slowing global warming," *Review of Environmental Economics and policy*, 2007, *1* (1), 26–44.

Olson, Mancur Jr., *The Logic of Collective Action: Public Goods and the Theory of Groups*, Cambridge, Mass.: Harvard University Press, 1965.

Parry, Martin L, *Climate Change 2007: impacts, adaptation and vulnerability: contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel on Climate Change*, Vol. 4, Cambridge University Press, 2007.

Patt, Anthony G, Detlef P van Vuuren, Frans Berkhout, Asbjørn Aaheim, Andries F Hof, Morna Isaac, and Reinhard Mechler, "Adaptation in integrated assessment modeling: where do we stand?," *Climatic Change*, 2010, *99* (3-4), 383–402.

Rezai, Armon and Frederick van der Ploeg, "Intergenerational inequality aversion, growth and the role of damages: Occams rule for the global carbon tax," *Journal of the Association of Environmental and Resource Economics*, 2015, (3), 493–522.

Samuelson, Paul A, "The Pure Theory of Public Expenditure," *The Review of Economics and Statistics*, 1954, pp. 387–389.

Schumacher, Ingmar, "The Aggregation Dilemma," Technical Report, Department of Research, Ipag Business School 2014.

Sen, Amartya Kumar, *Commodities and Capabilities: Professor Dr. P. Hennipman Lectures in Economics, 1982 Delivered at the University of Amsterdam*, Oxford University Press, 1987.

Stern, Nicholas, *The economics of climate change: the Stern review*, Cambridge University Press, 2007.

Tol, Richard SJ, Samuel Fankhauser, and Joel B Smith, "The scope for adaptation to climate change: what can we learn from the impact literature?," *Global Environmental Change*, 1998, *8* (2), 109–123.

Tsur, Yacov and Amos Zemel, "Policy tradeoffs under risk of abrupt climate change," *Journal of Economic Behavior & Organization*, 2016.

_ **and Cees Withagen**, "Preparing for catastrophic climate change," *Journal of Economics*, 2013, *110* (3), 225–239.

van der Ploeg, Frederick and Aart de Zeeuw, "Climate policy and catastrophic change: be prepared and avert risk," Technical Report, European University at St. Petersburg, Department of Economics 2013.

Yohe, Gary and Kenneth Strzepek, "Adaptation and mitigation as complementary tools for reducing the risk of climate impacts," *Mitigation and Adaptation Strategies for Global Change*, 2007, *12* (5), 727–739.

Zeeuw, Aart De and Amos Zemel, "Regime shifts and uncertainty in pollution control," *Journal of Economic Dynamics and Control*, 2012, *36* (7), 939–950.

Zemel, Amos, "Adaptation, mitigation and risk: An analytic approach," *Journal of Economic Dynamics and Control*, 2015, *51*, 133–147.