

The Aggregation Dilemma

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Abstract

The results in this paper show that the level of aggregation used in a social welfare function matters significantly for policy analysis. Using climate change as an example, it is shown that, under the mild and widely-accepted assumptions of asymmetric climate change impacts and declining marginal utility, an aggregation dilemma may arise that dwarfs most other policy-relevant aspects in the climate change cost-benefit analysis. Estimates based on the RICE-99 model (Nordhaus and Boyer 2000) suggest that aggregation leads to around 26% higher total world emissions than those from a regional model. The backstop energy use would be zero in the model which aggregates consumption in utility, while it would be 1.3% of Gross World Product in a regionally-disaggregated version. In general we observe that richer countries will be required to undertake stronger efforts toward climate policy based on the aggregated utility social welfare function and compared to both the aggregated utility function with Negishi weights and the aggregated consumption function. We propose criteria that may aid in deciding on the level of aggregation one might wish to choose depending on both positive and normative criteria. Though the policy recommendations from fully aggregated models like the DICE model are always used as a benchmark for policy making, the results here suggest that this should be done with the reservations raised by the Aggregation Dilemma in mind.

Keywords: Aggregation Dilemma; social welfare function; Integrated Assessment Models; climate policy.

JEL classification: Q54; Q58

1 Introduction

Whenever a large-scale policy is evaluated, then a policy maker tends to use a social welfare function relying on some level of aggregation. Lower levels of aggregation are applied to local issues like waste management, higher ones for more regional problems such as river pollution or for country-wide policies like emission standards. In general, the highest levels of aggregation tend to be used for studies related to climate change. However, the way a policy maker aggregates individuals, regions or countries in the social welfare function is by no means an innocent choice and may fully drive the results of the climate change policy analysis. This paper shows that a social welfare function evaluated at different levels of aggregation, for example the individual, regional or world level, may lead to significantly different results when a policy maker studies optimal policies.

The main assumptions underlying the results in this paper are that climate change impacts agents asymmetrically, and that costs and benefits are evaluated using a utility function with declining marginal utility. In this case it is already well-known that the conditions under which a representative agent may exist are restrictive. However, the question is whether different levels of aggregation, e.g. at the world level, as is being done in the DICE model,¹ or the regional level, as is the case for the RICE model,² lead to different results. In addition, if the results are different, then the question is as to how quantitatively important are those differences. This paper looks into these question using a stylized mathematical model, and then attempts to forward a quantification of the problem. In this respect, the current paper raises a note of caution when deciding on the level at which one aggregates units in a social welfare function. Obviously, we prefer to aggregate for many reasons like data availability or reduction in complexity. Nevertheless, we have to be aware of the costs of aggregation, and one of the main costs is that a higher level of aggregation tends to reduce the marginal willingness to undertake climate policy. We call this the ‘Aggregation Dilemma’. With this in mind, the results presented in this paper show that the Aggregation Dilemma can readily dwarf most other policy-relevant issues like discounting, risk aversion or climate sensitivity. We also show that the other policy-relevant issues strongly interact with the Aggregation Dilemma. For example, we find that both a lower discount rate as prescribed by e.g. Stern (2007), and a faster decline in the marginal utility (i.e. a lower in-

¹Other integrated assessment models at this level of aggregation are the ENTICE-BR (Popp 2006), DEMETER-1CCS (Gerlagh 2006) and MIND model (Edenhofer et al. 2005).

²Other integrated assessment models at this level of aggregation are the models FEEM-RICE (Bosetti et al. 2006a), FUND (Tol 1997), MERGE (Manne and Richels 2005), WITCH (Bosetti et al. 2006b), CETA-M (Peck and TJ 1999), GRAPE (Kurosawa 2004) or AIM/Dynamic Global Masui et al. (2006). For more information on these models the reader is referred to Stanton et al. (2009).

tertemporal elasticity of substitution) both increase the Aggregation Dilemma. In general we observe that richer countries will be required to undertake stronger efforts toward climate policy based on the aggregated utility social welfare function and compared to both the aggregated utility function with Negishi weights and the aggregated consumption function. We suggest that these differences cannot only arise due to income differences but should, at least partly, be due to towards differences in the effectiveness of regional climate action. Though the policy recommendations from fully aggregated models like the DICE model are always used as a benchmark for policy making, the results here suggest that this should be done with the reservations raised by the Aggregation Dilemma in mind.

There are other studies that have already looked at the role that the social welfare function plays for climate policy. Prominent examples are Tol (2002), who looked at risk aversion, inequality aversion, time discounting (Tol 1999), equity weighing within the social welfare function (Fankhauser et al. 1997), different types of social welfare function (d'Arge et al. 1982, Tol 2001), or the interaction between transfers and climate policy (Sandmo 2007, Anthoff 2011). An excellent overview can also be found in Botzen and van den Bergh (2014). All these issues are clearly important for policy making. Also, some of these strongly interact with the Aggregation Dilemma that we discuss in the following sections. As a result, these articles should be viewed as raising complementary issues that any policy maker needs to keep in mind when evaluating climate policy.

The plan of the paper is the following. In section 2 the paper builds up the intuition that underlies the 'Aggregation Dilemma' using a highly stylized mathematical model. The model helps to show that only few, well-accepted assumptions are necessary to induce the Aggregation Dilemma. In section 2.1 I develop a general result that is able to show two main issues: One, under an extreme yet realistic assumption, the marginal willingness to undertake climate policy is infinite when policy is determined based on the disaggregated model. In contrast, an aggregated model would have a bounded marginal willingness to undertake climate action. Two, I show under which (rather realistic) conditions the willingness to undertake climate action reaches world GDP in the disaggregated model. In the aggregated case, the conditions for this are extremely restrictive and unrealistic. In section 3 I discuss various lessons that we may draw from the results presented above. I provide an empirical estimate of the Aggregation Dilemma based on a minimally-modified RICE model. In addition, I look into the positive and normative implications that arise from the Aggregation Dilemma. Finally, section 4 concludes with some lessons one may wish to take away from this study.

2 Building intuition

In this section I want to build the intuition for the more general result that I provide later. The idea is to discuss the basic intuition behind the Aggregation Dilemma and demonstrate the implications using a highly stylized mathematical model.

At the onset it is useful to frame the problem in the current climate policy debate. Thus, I would like to invite the reader to think about the way climate policy is tackled these days. The predominant approach is to rely on a model that combines economic and climate feedbacks, the so-called integrated assessment models. The class of models that is of particular interest here is the welfare maximizing one,³ with the well-known aggregate DICE and the regionally-disaggregated RICE models of Nordhaus and his co-authors (2010, 2013) as the front runners. The focus will be on what is called the optimal solution, thus the solution where a single policy maker finds the best possible outcome excluding additional policy targets (like the 2 °C target) or problems of cooperation. As such, by focusing on only the optimal solution and abstracting from additional policy-relevant targets, we are able to gain in clarity.

The original DICE model (Nordhaus 1993) and its currently latest version (Nordhaus and Sztorc 2013) are aggregated consumption, integrated assessment models. There are economic and climatic feedbacks, and a policy maker evaluates the optimal allocations that maximize utility subject to the constraints, which are aggregated economic and climate feedback equations. The world is modeled as one unit, with all individual consumption being aggregated, averaged across individuals, and then evaluated in a utility function. Now, the matter would indeed be trivial and this model would be able to well capture the best possible climate action if regional-specific differences in climate damages would be sufficiently small. In this case, the conditions for the existence of a representative agent would be fulfilled. A representative agent model is one where the aggregated action of all individuals can be represented by the actions of one agent alone. However, simply aggregating across economic and climate constraints implies the existence of a representative agent only if all individuals are the same.⁴ I want to draw attention to the limits of this modeling approach by showing important differences in the optimal allocations if climate impacts are not uniform across individuals, and thus the problem with the usage of ‘the average’.

For simplicity, we shall here assume that all individuals are the same except that they face different degrees of climate change. This is our substantial assumption that drives the results

³See the review Stanton et al. (2009) for other classes, like general equilibrium models or cost minimization ones.

⁴See also Kirman (1992), who suggests that a representative agent framework is generally “unjustified and leads to conclusions which are usually misleading and often wrong.” (p.117) Further discussions are in Stanton et al. (2009) or Stanton (2011).

presented in this article. Nevertheless, it should be clear that this assumption is a by now well-described empirical regularity and the fact that there are substantial differences in local or regional impacts of climate change has been clearly shown in the contribution of Working Group II to the Fourth Assessment Report of the IPCC, see Parry et al. (2007). This report describes the various regional impacts of climatic changes. Among many other, these points stand out: “By mid-century, annual average river runoff and water availability are projected to increase by 10-40% at high latitudes and in some wet tropical areas, and decrease by 10-30% over some dry regions at mid-latitudes and in the dry tropics.” In terms of flooding, “[t]he numbers affected will be largest in the mega-deltas of Asia and Africa while small islands are especially vulnerable.” Similarly, “[s]tudies in temperate areas have shown that climate change is projected to bring some benefits, such as fewer deaths from cold exposure. Overall it is expected that these benefits will be outweighed by the negative health effects of rising temperatures worldwide, especially in developing countries.” Again, “[c]limate change is expected to have some mixed effects, such as a decrease or increase in the range and transmission potential of malaria in Africa.” Finally, “[i]t is projected that crop yields could increase up to 20% in East and South-East Asia while they could decrease up to 30% in Central and South Asia by the mid-21st century.” This led the IPCC to one of their main conclusions: “Costs and benefits of climate change for industry, settlement and society will vary widely by location and scale. In the aggregate, however, net effects will tend to be more negative the larger the change in climate.” Thus, the IPCC clearly states that there are strong differences in local or regional impacts, with some potentially positive ones and other negative ones, while the overall, aggregate effect should be negative.

It should be emphasized that the potential importance of individual-specific climate impacts for policy decisions has been foreseen in much of the literature. This is the reason why e.g. Nordhaus and Yang (1996) developed a regionally-disaggregated model, the RICE model. When they introduced the first version of the RICE model, they noted that “[g]lobally aggregated models have the shortcoming of losing many of the interesting and important details of different regions.” Some of these interesting and important details are obviously issues related to cooperation across regions, but the one we shall concern ourselves here is the region-specific difference in the climate impacts. What we emphasize here is that the RICE model, like all other regionally-disaggregated integrated assessment models (FUND, FEEM-RICE, MERGE, etc.), is only an model at yet another specifically chosen level of aggregation. For example, even the currently latest version of the RICE model (Nordhaus 2010) represents only 13 regions, with all of Africa making up one of these. Nevertheless, there is sufficient evidence (see above and Parry et al. (2007) or Mendelsohn et al. (2006)) indicating a variety of climate change impacts even

within Africa, with some regions potentially benefiting from climate change and others losing out. The question again is as to whether or not these regionally-different impacts from climate change *should* lead to different optimal policy actions compared to the suggested policies from the RICE or DICE model, or thereby any welfare-maximizing integrated assessment model.

We now pin down the exact assumptions that we rely on and ponder over the expected results. Firstly, we assume that agents have a concave utility function, thus implying that additional units to consumption (or whatever makes up their utility) lead to diminishing increases in utility. I would say that this assumption is uncontroversial, and all welfare-maximizing models of climate change rely on this. Secondly, climate impacts differ between agents, where by agents we may mean anything from households, counties or countries to regions. Again, this assumption should be undebatable and comes from the studies of the IPCC (Parry et al. (2007)). There are two periods, an initial one where climate policy can be undertaken, and an impact period, where agents potentially benefit from the climate action in the initial period. Assuming agents to be otherwise identical, we are searching for the optimal climate action from a policy maker's perspective given different levels of aggregation in the social welfare function.

Purely based on intuition, let us anticipate some of the mathematical results that follow. We shall use two extreme approaches. In what we shall call the aggregated consumption framework, the consumption from all agents gets summed and then evaluated in one utility function. We dub the other approach the aggregated utility framework, in which all individual utilities of all agents are summed together. In this second case an optimal solution will equalize marginal utility across all agents and the two periods. Since all agents in period one have the same income and the same preferences, then they will all undertake the same level of climate action.

There are two different means of climate action. One would be adaptation expenditure, which is individual-specific. Since individuals in period two are impacted non-uniformly, then more adaptation expenditure will be allocated to those individuals which are subjected to stronger climate impacts. In contrast, in the aggregated consumption framework, only the marginal utility of period one will be equalized to the marginal utility of period two. Since we evaluate the aggregate consumption level⁵, then marginal utility in the second period will be lower than in the aggregated utility framework. Consequently, the optimal adaptation efforts in the aggregated consumption framework should be less or equal to the optimal adaptation efforts in the aggregated utility one. As a result, climate impacts get averaged out in the aggregate consumption framework and the advised climate action may be understating the optimal one when all agents count individually.

⁵There is no difference in this framework between evaluating the average consumption level and the aggregate consumption level.

Another potential climate action is abatement expenditure, which has a public good character and affects all individuals. In this case we would again expect the aggregate utility model to see a higher optimal level of climate action than the aggregate consumption model, simply because the aggregate consumption model has, for a given level of climate action, always a lower second period marginal utility than the average marginal utility in the second period of the aggregate utility model, a result that follows directly from Jensen's inequality.

As an additional point, imagine that one agent is faced with such a strong climate impact that it would make his wealth drop to zero in period two. In this case the marginal willingness to pay for climate action should tend to infinity, but only in the aggregate utility framework. In contrast, under rather weak conditions, the aggregated consumption model may suggest that a corner solution with zero climate action may be optimal. This result is akin to Weitzman's (2009) Dismal Theorem, but does not require fat tails. Instead, what we simply require is that there exists at least one agent (may it be a household, county, country or region) who loses everything due to climate change, and a policy maker who evaluates aggregated utility instead of aggregated consumption.

At this point we would also like to note that equity weighting, as e.g. suggested by Fankhauser et al. (1997) or more recently Anthoff and Tol (2010) and Anthoff et al. (2009), tends to increase the Aggregation Dilemma, in the sense that the gap between the aggregated consumption model and the aggregated utility model is widened. This occurs since equity weights place more emphasis on those damages that occur in poorer countries.

Foreseeing some of the main results, what we thus should expect is that the choice of units, or the way we aggregate consumption or utility into a social welfare function, may fully drive the optimal level of climate action. Readers less interested in the mathematical aspects of the Aggregation Dilemma may skip the next section and proceed directly to section 3.

2.1 A simple model

A simple model should help in illustrating the points raised above. For simplicity we take a two period⁶ model, where an agent⁷ has utility $u(\cdot)$ over consumption in period one c_1 and period two c_2 . Wages $w > 0$ in period 1 and 2 are given, and period two wages grow by rate $g > 0$. There is a shock on wages in period 2 which comes in proportion to wages, ψw , with $\psi > 0$. The agent can curb the effect of the shock by investing in mitigation/adaptation in

⁶The subsequent results fully extend to any multiple-period model. For simplicity we neglect discounting, too. It only affects our results quantitatively.

⁷We shall talk about an agent here, but this can also refer to a region, a nation, a coalition, or alike.

period 1, given by $A \geq 0$. Thus, in period 1 the constraint may be written as $w - A = c_1$, while the period 2 constraint is given by $(1 + g)w - \psi w + A = c_2$. We obviously assume non-negativity constraints on consumptions across individuals and time periods. We shall work with the following assumptions.

A 1 We assume that $u : c \rightarrow R$, with $u'(\cdot) > 0$, $u''(\cdot) < 0$, $\lim_{c \rightarrow 0} u'(c) = \infty$.

A 2 We assume that $\psi w \geq A$.

Assumption 2 implies that transfers to period 2 cannot exceed the damages from climate change.

As a result of the maximization problem defined above and the assumptions taken, the agent maximizes

$$U(c_1, c_2) = u(c_1) + u(c_2), \quad (1)$$

and the constraints are given by

$$w - A = c_1, \quad (2)$$

$$(1 + g - \psi)w + A = c_2. \quad (3)$$

Substituting the constraints into the utility function and maximizing with respect to A yields⁸

$$u'_1 \geq u'_2, \quad (4)$$

or with equality if $A > 0$.

Solving for abatement explicitly gives us

$$A^{*b} = \min \left\{ \max \left\{ \frac{\psi - g}{2} w, 0 \right\}, w \right\}.$$

As a result, we obtain that the optimal mitigation/adaptation effort is increasing in the climate change damages, decreasing in the growth rate of the economy, is zero if the future generations have more wealth than the current generation, and tends to its maximum of w when $2 + g \leq \psi$.

We now summarize the important points to take away.

Result 1 (Baseline model) *If the policy maker solves the baseline model given by equations (1), (2) and (3), then there will be a corner solution with $A^{*b} = 0$ in abatement if $g \geq \psi$, while abatement will tend to its maximum of $A^{*b} \rightarrow w$ for $2 + g \leq \psi$.*

⁸We denote first derivatives by u' , second derivatives by u'' , and subscripts 1 and 2 refer to the dates.

It should be clear that this model is gauged towards a simple condition that insures both a corner solution in abatement at zero, as well as one where abatement reaches its potential maximum. The essential idea is to show that, depending on the way one formulates the social welfare, the current generation should do nothing or little *if* it addresses the climate change problem by solving an aggregated consumption framework. Obviously, several extensions will strengthen or weaken the condition under which the current generation will stay inactive⁹. Instead, we would like to take the reader into a slightly different direction, and place more emphasis on the unit of aggregation in a the social welfare function and the resulting optimal policy recommendations.

Let us, thus, now assume that the generations are made up of two sub-populations, which we for simplicity dub population *a* and *b*. Total wealth is split up equally across both sub-populations, such that $w/2 = w_a = w_b$. Without loss of generality, let us assume that population *a* is affected more strongly by climate change than population *b*, with coefficient $\psi_a > \psi > \psi_b$, but in total both populations have the same loss as it was in the baseline model above. We state this more clearly in the next assumption.

A 3 *We assume that $\psi w = (\psi_a + \psi_b)w/2$.*

What is important about this assumption is really that it allows us to compare our subsequent results to the baseline model in the sense that we investigate whether and when our result above is augmented if we allow for different climate change impacts in the sub-populations, while the average climate change impact stays constant. Let us also note that we allow for negative ψ_b here, which would imply a positive climate change impact on sub-population *b*.¹⁰ Furthermore, both sub-populations can abate in both sub-populations of the next period, where e.g. A_{ab} is the investment of sub-population *a* into sub-population *b* in period 2.

Our simple model above then can be solved in two ways. We can, firstly, assume that abatement decisions are taken by a representative agent that aggregates consumption, then evaluates this in utility, and then solves the decision problem of the generations, or we may assume that a policy maker evaluates the sum of the utilities of each sub-population. We start with the ag-

⁹For example, if we assume that the policy maker discounts future welfare, then this will weaken the conditions, in the sense that they will be relaxed, since now future welfare is evaluated as being lower than current welfare. In addition, allowing for a trade-off between reductions in consumption, increases in abatement, and the effect of consumption on future net income, is likely to strengthen the result. Technical change will ease the condition for a corner solution and will thus make it more likely. With another framework in mind, cultural changes (Schumacher 2013) or endogenous preferences (like pollution perception Schumacher and Zou (2008)) may also change the condition that leads to this corner solution.

¹⁰This is, for example, consistent with some regions in the US, where e.g. farmers are expected to benefit from climate change, see the IPCC report, Parry et al. (2007).

gregated consumption model¹¹, where a policy maker aggregates consumption in utility. This would, for example, correspond to the basic setting of the DICE model. This model can be written as

$$U(c_1, c_2) = u(c_{1a} + c_{1b}) + u(c_{2a} + c_{2b}), \quad (5)$$

and the constraints are given by

$$w/2 - A_{aa} - A_{ab} = c_{1a}, \quad (6)$$

$$w/2 - A_{ba} - A_{bb} = c_{1b}, \quad (7)$$

$$(1 + g - \psi_a)w/2 + A_{aa} + A_{ba} = c_{2a}. \quad (8)$$

$$(1 + g - \psi_b)w/2 + A_{ba} + A_{bb} = c_{2b}. \quad (9)$$

Simplifying and substituting into equation (5) gives us four equivalent first-order conditions

$$u'_1 \geq u'_2, \quad (10)$$

which clearly is an overidentified system. We pick up *one* solution¹², namely

$$A_{ij}^{*c} = \max \left\{ \min \left\{ \max \left\{ \frac{\frac{1}{2}(\psi_a + \psi_b) - g}{8} w, 0 \right\}, w/2 - A_{i,-j}^* \right\}, 0 \right\}.$$

Since all solutions for A_{ij}^{*c} in this aggregated consumption model are equal, then the solution above can be reduced to

$$A_{ij}^{*c} = \max \left\{ \min \left\{ \max \left\{ \frac{\frac{1}{2}(\psi_a + \psi_b) - g}{8} w, 0 \right\}, w/4 \right\}, 0 \right\}.$$

Also, this allows us to scale the solutions, and noting that $\frac{1}{2}(\psi_a + \psi_b) = \psi$, we can finally obtain

$$\sum A_{ij}^{*c} = \min \left\{ \max \left\{ \frac{\psi - g}{2} w, 0 \right\}, w \right\},$$

¹¹In this setup, the results of the aggregated consumption model coincide with those from the average consumption model, where $U(c_1, c_2) = 2u(\frac{c_{1a} + c_{1b}}{2}) + 2u(\frac{c_{2a} + c_{2b}}{2})$.

¹²There are, indeed, infinitely many solutions to this problem since it is over-identified. However, we pick up what we suppose is the ‘natural’ solution. In effect, our main result in this part is about the sums of A in each sub-population, and not the individual contributions. Thus, whatever solution is picked up, as long as it satisfies equation (10), then our result below obtains. In other words, the result is about the aggregate contributions, while it does not matter here how precisely the individual contributions are combined linearly.

which obviously leads to an identical result as the one in the baseline model, with $\sum A_{ij}^{*c} = A^{*b}$, for $i, j = a, b$. We now note that this result applies irrespectively of the level of ψ_a and ψ_b , as long as their linear combination equals ψ . Thus, we come to our second result.

Result 2 (Aggregated consumption model) *If the policy maker aggregates consumption of different sub-populations, then the optimal abatement level will be the same as in the baseline model.*

This result applies irrespectively of the extent of climate change in each region, and comes about since the policy-maker essentially treats the individuals as one aggregated one, just like it was the case in the baseline model above. Though most economists are unlikely to be surprised by this result, the next paragraphs should convince the reader of the deeper policy dilemma that I wish to place attention on.

Assume now that a policy maker aggregates the utility (in contrast to consumption) of each sub-population. This will require to maximize

$$U(c_1, c_2) = u(c_{1a}) + u(c_{1b}) + u(c_{2a}) + u(c_{2b}), \quad (11)$$

with the constraints still being given by equations (6) to (9). This maximization problem gives rise to four first-order conditions, given by

$$u'_{1A_{aa}} \geq u'_{2A_{aa}}, \quad (12)$$

$$u'_{1A_{ab}} \geq u'_{2A_{ab}}, \quad (13)$$

$$u'_{1A_{ba}} \geq u'_{2A_{ba}}, \quad (14)$$

$$u'_{1A_{bb}} \geq u'_{2A_{bb}}. \quad (15)$$

These four first-order conditions hold with equality for interior solutions. The solution to this problem is to set $A_{aa} = A_{ba}$ and $A_{ab} = A_{bb}$. This solution equalizes the marginal utilities in period 1. In addition, I need to have the result that the marginal utilities in period 1 are equal to the marginal utilities in period 2. As a consequence, period 2 marginal utilities will be equal. I

thus end up with the conditions

$$A_{aa}^{*u} = \max \left\{ \min \left\{ \max \left\{ (\psi_a - g) \frac{w}{8}, 0 \right\}, w/2 - A_{ab}^{*u} \right\}, 0 \right\}, \quad (16)$$

$$A_{ab}^{*u} = \max \left\{ \min \left\{ \max \left\{ (\psi_b - g) \frac{w}{8}, 0 \right\}, w/2 - A_{aa}^{*u} \right\}, 0 \right\}, \quad (17)$$

$$A_{ba}^{*u} = \max \left\{ \min \left\{ \max \left\{ (\psi_a - g) \frac{w}{8}, 0 \right\}, w/2 - A_{bb}^{*u} \right\}, 0 \right\}, \quad (18)$$

$$A_{bb}^{*u} = \max \left\{ \min \left\{ \max \left\{ (\psi_b - g) \frac{w}{8}, 0 \right\}, w/2 - A_{ba}^{*u} \right\}, 0 \right\}. \quad (19)$$

By assumption 3 I know that $\psi_a > \psi > \psi_b$. I can therefore distinguish between three sub-regimes.

In sub-regime 1 I have that $g > \psi_a (> \psi_b)$, and as a result all $A_{ij}^{*u} = 0$. This is a stronger condition than for the previous models, implying that a corner solution in abatement is now less likely.

In sub-regime 2, I have $\psi_a > g > \psi_b$ and optimal allocations will be given by

$$A_{aa}^{*u} = A_{ba}^{*u} = \min \left\{ (\psi_a - g) \frac{w}{8}, w/2 \right\}, \quad (20)$$

$$A_{ab}^{*u} = A_{bb}^{*u} = 0, \quad (21)$$

Total abatement expenditure will, therefore, be given by $A_{aa}^{*u} + A_{ba}^{*u} = \min \left\{ (\psi_a - g) \frac{w}{4}, w \right\}$. It is possible to show that this is larger than abatement expenditure in both the baseline and the aggregated consumption model.¹³

In sub-regime 3 I have that $(\psi_a >) \psi_b > g$. In this case it is possible to obtain, depending on the parameter configurations, the following sets of optimality conditions, for $i = a, b, j = a, b$,

1. if $\psi < 2 + g$, and $\psi_i < 4 + g$ and $\psi_{-i} < 4 + g$, then $A_{ii}^{*u} = \frac{\psi_i - g}{8} w$ and $A_{i,-i}^{*u} = \frac{\psi_{-i} - g}{8} w$, with $\sum A_{ij}^{*u} = \frac{\psi - g}{2} w$.
2. if $\psi_i > 2 + g$ and $\psi_{-i} > 2 + g$, then $A_{ii}^{*u} = A_{i,-i}^{*u} = w/4$, with $\sum A_{ij}^{*u} = w$.
3. if $\psi > 2 + g$ and $\psi_i < 2 + g$, then $A_{ii}^{*u} = \frac{\psi_i - g}{8} w$ and $A_{i,-i}^{*u} = \frac{4 - \psi_i + g}{8} w$, with $\sum A_{ij}^{*u} = w$.
4. if $\psi > 2 + g$ and $\psi_{-i} < 2 + g$, then $A_{ii}^{*u} = \frac{4 - \psi_{-i} + g}{8} w$ and $A_{i,-i}^{*u} = \frac{\psi_{-i} - g}{8} w$, with $\sum A_{ij}^{*u} = w$.

I am now ready to summarize the conditions above in our third result, which should make the difference to the previous ones explicit and give rise to what I call the *social welfare aggregation dilemma*.

¹³It is larger since $(\psi_a - g) \frac{w}{4} > (\psi - g) \frac{w}{2}$ by assumption of sub-regime 2, namely $\psi_b < g$.

Result 3 (Aggregated utility model) *If the policy maker aggregates utility of different sub-populations and then maximizes function 11 subject to equations (6) to (9), then there will be a corner solution with $A_{ij}^{*u} = 0$ if $g > \psi_a (> \psi_b)$. If $\psi_a > g$, then $\sum A_{ij}^{*u} \geq A^{*c}$.*

As a consequence, the result that one can see here is that, if a policy maker aggregates utility instead of consumption, then the parameter condition for a corner solution in abatement is stronger (meaning the set of parameters that leads to a corner solution $A^{*u} = 0$ is smaller), and, in case there is an interior solution in abatement, then the abatement effort will be at least as strong in the aggregated utility model as in the aggregated consumption one. In the next sections I will show that this is a result that is not particular to this specific model but a general one that applies in a multitude of settings. Furthermore, I will discuss implications and conclusions that one may draw from this analysis.

2.2 A general result on the Aggregation Dilemma

Let us assume there exist N individuals, each having an endowment of w in period 1 and of $(1+g)w$ in period 2. Each individual will be affected by climate change that comes in proportion to period 1 wages, and each individual is affected differently. We can order individuals and the impact on them according to $\psi_i > 0$, $i = 1, \dots, N$, where $\psi_1 < \psi_2 < \dots < \psi_N$. Thus, individual 1 will see the weakest impact from climate change¹⁴, while individual N will be impacted the most, given by ψ_N . The average impact is given by $\psi = \frac{1}{N} \sum_i \psi_i$. We assume that all ψ_i 's are a function of the total abatement effort of period 1 individuals, such that $\psi_i(\sum_i A_i)$. We take it that the following conditions apply to all function ψ_i .

A 4 *Function $\psi_i(\sum_i A_i)$ follows $\psi_i(0) > 0$, $\psi'_i(\sum_i A_i) < 0$, $\psi''_i(\sum_i A_i) > 0$, $\psi_i(\infty) = 0$ and $\psi'_i(0) < \infty$.*

Thus, climate damages come as a share of income, and total abatement expenditure diminishes this impact at a decreasing rate. Climate damages tend to zero for very large sums of abatement expenditure, and the marginal benefit at zero abatement expenditure is finite.

We will furthermore work with the following assumption.

A 5 *$\psi'_i(\sum_i A_i) = \psi'_j(\sum_i A_i)$, $\forall i = 1, \dots, N$ and all $j = 1, \dots, N$.*

¹⁴One could also allow for a potentially positive impact, but would then have to re-write the model slightly. Thus we restrict ourselves, without loss of generality, to $\psi_i > 0$.

The difference to our previous model is that we now allow the existence of N agents (before we had two), and that mitigation effort is not region-specific or individual-specific but total mitigation effort has an impact on damages. Thus, the model here brings us closer to abatement or mitigation efforts in the standard sense, while in the model above we were more closely dealing with adaptation efforts.

Our two maximization problems then are as follows. The **aggregated consumption model** is given by

$$U\left(\sum_i c_{1i}, \sum_i c_{2i}\right) = u\left(\sum_i c_{1i}\right) + u\left(\sum_i c_{2i}\right), \quad (22)$$

which should be maximized subject to

$$w/N = c_{1i} + A_i, \quad (23)$$

$$c_{2i} = \left(1 + g - \psi_i\left(\sum_i A_i\right)\right) w/N, \quad (24)$$

which hold $\forall i = 1, \dots, N$.

The first-order conditions will be given by

$$-u_1^{c'} \leq u_2^{c'} \frac{w}{N} \sum_i \psi_i^{c'}, \quad (25)$$

for all $i = 1, \dots, N$, where a superscript c refers to the first-order conditions from the aggregate consumption model.

In contrast, the **aggregated utility model** is given by

$$U\left(c_{1i}, \dots, c_{1N}, c_{2i}, \dots, c_{2N}\right) = \sum_i u(c_{1i}) + \sum_i u(c_{2i}), \quad (26)$$

which should be maximized subject to

$$w/N = c_{1i} + A_i, \quad (27)$$

$$c_{2i} = \left(1 + g - \psi_i\left(\sum_i A_i\right)\right) w/N, \quad (28)$$

which hold $\forall i = 1, \dots, N$.

The first-order conditions in this case will be given by

$$-u_{1i}^{u'} \leq \frac{w}{N} \sum_i u_{2i}^{u'} \psi_i^{u'}, \quad (29)$$

for all $i = 1, \dots, N$, with a superscript u denoting the first-order conditions from the aggregate utility model.

If we now compare the two sets of first-order conditions from the aggregated consumption model (eq. (25)) and from the aggregated utility model (eq. (29)), then the main difference that we observe comes from the fact that in the aggregated consumption model we have only the second-period marginal utility of aggregated consumption, while in the aggregated utility case we have the *sum* of all individual's second-period marginal utilities.

Proposition 1 *Under Assumption 4 and 5, we find that*

$$\sum_i u_{2i}^{u'} \psi_i^{u'} \geq u_2^{c'} \sum_i \psi_i^{c'}.$$

Proof of Proposition 1 *Proof by contradiction. One can show that, for interior solutions, $w_i^{c'} \geq w_i^{u'}$, where superscript c refers to the first order conditions from the aggregate consumption model, and superscript u to those from the utility model, is impossible since this leads to a contradiction when comparing second period utilities. This is easily shown via the Jensen's inequality. ■*

We thus show that our results from above are preserved in this more general setting¹⁵. Basically, as long as mitigation actions are undertaken because agents are strongly impoverished due to climate change, then this will drive mitigation actions in the aggregated utility model, while it may lead to little mitigation actions, or none at all, in the aggregated consumption model.

The result crucially hinges on the assumed asymmetry in the climate change impact. Quite clearly, if we assume this asymmetry away, then both the aggregated consumption and the aggregate utility model lead to equivalent results.

¹⁵If A4 is not satisfied, then there are specific cases under which Proposition 1 does not hold. For example, if one region is rich but mitigation effects in that region have a strong marginal impact, then the sign may be reversed. However, what we suggest is that in case impoverishment is the driver of mitigation behavior, that means if climate change is strongly impacting one region or agent, then this may fully drive mitigation actions in the aggregated utility case.

2.3 Two extreme yet realistic cases

Let us take the analysis above yet one step further and introduce the following two assumptions.

A 6 We assume that $\exists k \in \mathbb{Z}(N)$, s.th. $\forall i \geq k, \psi_i(0) \geq 1 + g$.

This implies that, in case of zero mitigation action, agent k , and any agent more strongly impacted than agent k , will lose all wealth in period 2.

A 7 Assume that $\exists h \in \mathbb{Z}(N)$, s.th. $\forall i \geq h, \psi_i(\sum_i w_i) \geq 1 + g$.

This assumption states that, even if all agents spend all their income on mitigation, all agents ranked after agent h will still lose all their wealth in period two. Thus, the difference between A6 and A7 is that in the first assumption we take it that there exists at least one agent that will lose everything if no mitigation effort is undertaken, while the second assumption implies that there exists at least one agent that will lose everything even if as much mitigation effort is being done as is physically possible.

Proposition 2 Assuming A6 implies that the marginal benefit to adaptation expenditure is $\sum_i u_{2i}^{u'} \psi_i^{u'} = \infty$, while $u_2^{c'} \sum_i \psi_i^{c'} < \infty$. Assuming A7 implies that the marginal benefit to adaptation expenditure is $\sum_i u_{2i}^{u'} \psi_i^{u'} = \infty$ at any feasible level of adaptation expenditure, while $u_2^{c'} \sum_i \psi_i^{c'} < \infty$.

Proof of Proposition 2 Follows directly from A6 and A7. ■

We may thus conclude that, as long as there is at least one agent who is fully impoverished by climate change, then this agent will drive the marginal benefit of climate action in the aggregated utility model to infinity. In contrast, in the aggregated consumption model, this is clearly not the case since climate impacts get averaged (or summed) away.

Furthermore, if there exists at least one agent who is so strongly impacted by climate change that, even if all agents were to spend all their money on mitigation effort, this agent would still lose everything to climate change, then the willingness to undertake climate action would be infinite at every level of adaptation expenditure. This last result seems controversial in the sense that transfers could eliminate this result. Allowing for transfers in a regional public good model, Sandmo (2007) and Anthoff (2011) have shown that allowing for transfers may reduce climate action. For example, if A7 holds, then one can very well imagine that transfers could be a cheaper means of achieving equality in marginal utilities than climate action. However, this conclusion would also depend on whether we account for uncertainty or fat tails in climate change impacts, which may affect utility directly. Both additional issues can easily tip the scale towards climate action again.

3 Implications and discussions

The previous section shows that a cost-benefit analysis based on a social welfare function established via a simple aggregation of agents' consumption (as is e.g. being done in the DICE model) may lead to different results compared to aggregating agents' utility. The mathematical model shows that, even under fairly mild assumptions, the policy implications may be substantial and dwarf most other aspects of climate policy that have been deemed important in the recent studies. One obvious question is as to how important this result may be in reality, and whether it is possible to establish criteria that help us in deciding which conditions lead us to prefer the one or other approach.

3.1 Empirical estimate of the Aggregation Dilemma

As suggested above, the mathematical result suggests that under mild assumptions, the disaggregated utility model may potentially lead to an infinite marginal willingness to undertake climate policy. This stands in stark contrast to the aggregated consumption model, which may, under the same assumption, recommend no climate action at all. It is, thus, certainly of interest to investigate the empirical relevance of the theoretical result. In order to provide an empirically-relevant estimate of the Aggregation Dilemma, we minimally adapt the code for the RICE-99 model that Professor Nordhaus kindly provides.

First off though, it is clear that the RICE model by Nordhaus, or any currently available integrated assessment model, is already a model which is aggregated at a certain level. For example, the RICE-99 model aggregates the world into 13 regions. We have already argued above that even within regions such as Africa, some areas potentially benefit from climate change while others may be hit stronger. As a consequence, some of the climate change damages may already be averaged away, even in regional models like the RICE model. Hence, the results from regionally-aggregated models like the RICE model should fall in between the two extreme cases given by the aggregated utility model and the aggregated consumption model. Conclusively, the simulation results presented below, which are based on a modified RICE-99 model, should be viewed as a *lower* bound for the potential error of aggregating fully. Clearly, if this error then turns out to be sizable, it is reasonable to believe that aggregated integrated assessment models (like the DICE model) may prescribe a far too conservative climate policy than could be necessary.

We study three different scenarios. The first scenario is based upon the aggregated utility

social welfare function, which is defined as

$$U^{au} = \sum_T \sum_N 10 * R(T)P(T, N) \log \left(\frac{C(T, N)}{P(T, N)} \right). \quad (30)$$

Utility U^{au} is defined as the discounted ($R(T)$) sum of population-adjusted ($P(T, N)$) felicities, which are give by the logarithm of time and region-specific per capita consumption ($C(T, N)/P(T, N)$). This is equivalent to the utility function used in the RICE-99 model, except that we neglect Negishi weights. We neglect these as we would like to obtain a solution that corresponds as closely as possible to the aggregated utility model as defined above, and furthermore we want to avoid the ethical connotation underlying Neghishi weights.¹⁶ However, as all regional integrated assessment models rely on Negishi weighting, it seems reasonable to nevertheless study the impact of these in comparison to the unweighted social welfare function and the aggregated consumption function. Thus, we also study the potential differences that may arise through the use of Neghishi weights. Our second scenarios is therefore defined by

$$U^{auN} = \sum_T \sum_N 10 * R(T)P(T, N)W(N) \log \left(\frac{C(T, N)}{P(T, N)} \right). \quad (31)$$

where U^{auN} stands for the utility functional in the aggregated utility case with Negishi weights, and it corresponds fully to the social welfare function used in the RICE-99 model. The third scenario is the aggregated consumption model. For this we define the aggregated consumption social welfare function, which we denote as

$$U^{ac} = \sum_t 10 * R(T)P(T) \log \left(\sum_N \frac{C(T, N)}{P(T)} \right). \quad (32)$$

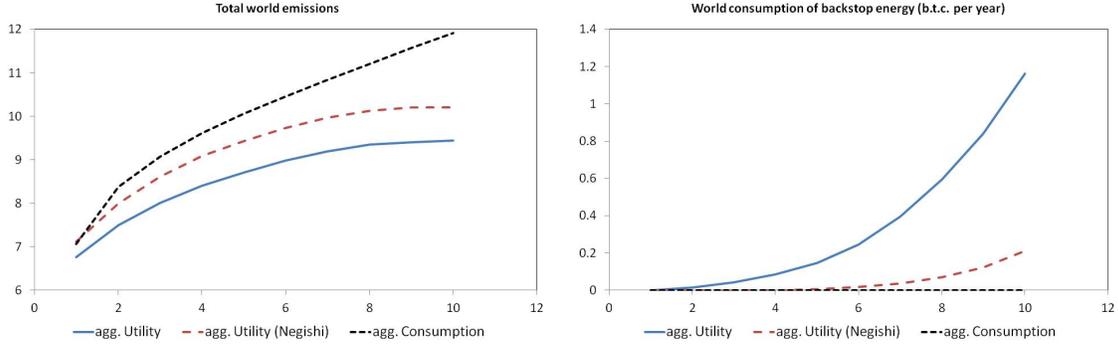
This social welfare function sums instantaneous felicity as a function of per capita world consumption, and for obvious reasons neglects Negishi weights.

The choice variables in this model are region-specific carbon emissions, the use of backstop energy, and per capita consumption. We present the simulations based on the policy maker's perspective, who searches for the optimal solution. The results of this exercise are then shown in Figure 1.

In the aggregated consumption model, total world emissions are up to 26% higher than in the aggregated utility model, and up to 16% higher compared to the aggregated utility model

¹⁶In this sense, we align ourselves with Kirman (1992), who suggests that a representative agent framework is generally “unjustified and leads to conclusions which are usually misleading and often wrong.” (p.117)

Figure 1: Integrated Assessment results (modified Rice-99 model)



with the Negishi weights, in each decade until the end of the century. Furthermore, the policy maker would use no backstop energy if he were to rely on the aggregated consumption model for policy evaluation. This stands in contrast to his use of backstop energy in both aggregated utility models, where the model without Negishi weights optimally allocates a maximum of 1.2% of the Gross World Product to the backstop use, while the model with Negishi weight allocates a maximum of 0.3%. In the aggregated utility model, the total amount of backstop energy used is roughly 7.5 times larger than in the aggregated utility model with Negishi weights. Overall, the Negishi weights tip the scale towards to needs of the richer regions, while the aggregate consumption model averages the climate damages away and leads to the least climate action.

World capital stocks in the aggregated utility models are marginally different, with the model with Negishi weights having a slightly higher capital stock. The world capital stock in the aggregated consumption model is roughly 10% higher compared to the one in the aggregated utility models. Consumption in all three models is nearly the same, with consumption in the aggregated consumption being slightly larger than in the other two models. In line with the results above, world CO₂ concentrations are the largest in the aggregated consumption model, followed by the aggregated utility model with Negishi weights, and then the aggregated utility model.

Sensitivity analysis of these results to generally discussed parameters in the integrated assessment literature, namely the discount rate and the intertemporal elasticity of substitution, suggest that a higher discount rate reduces the difference in both the total world emissions and the use of the backstop energy between the aggregated consumption and aggregated utility model. The Aggregation Dilemma should, therefore, be much larger under a low discount rate as prescribed by e.g. Stern (2007).

In contrast, a lower intertemporal elasticity of substitution changes the results of the aggre-

gated consumption model only marginally, while we observe large changes in the aggregated utility model. The use of the backstop energy is significantly higher, and total emission are much lower in the aggregated utility model if the intertemporal elasticity of substitution decreases. This result comes about since a lower elasticity of substitution places more weight on the worse off.

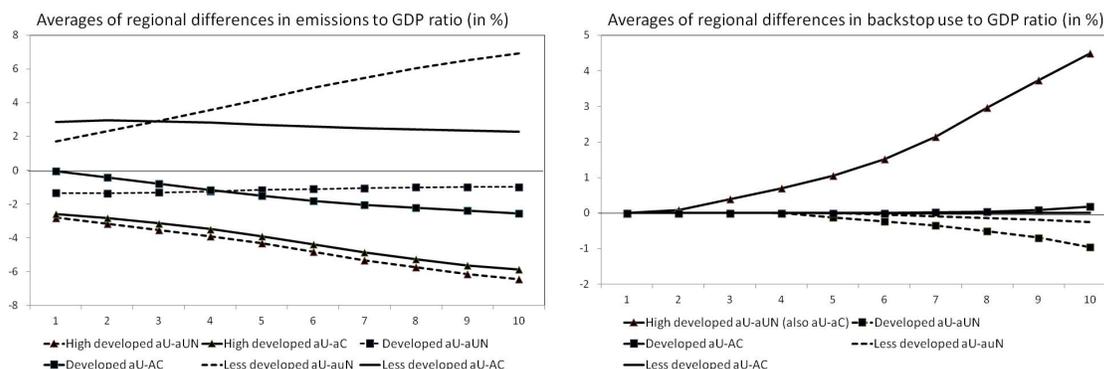
Overall, the current results add to the previous studies investigating the sensitivity of climate policy recommendations to widely-discussed parameters in the literature (see e.g. Stern 2007, Nordhaus 2007, Weitzman 2007), like the discount rate or the curvature of the utility function, in the sense that they show that under different levels of aggregation in the social welfare functions the importance of these parameters increases or declines. Thus, there is considerable interaction between these widely-discussed parameters and the Aggregation Dilemma.

Above we looked at the impact of aggregation on the totals in climate policy that a cooperative policy maker would choose. In Figure 2 we plot the regional climate actions, where, for simplicity of exposition, plot the averages of those regions that will act qualitatively similar. Thus, our *High developed* is made up of USA, Japan, Europe, other high income countries and high income OPEC country; the group of *Developed* countries is made up of Russia, Middle income, Low-Middle income and Eastern European countries; and the group of *Less developed* countries is made up of Low income countries, China, India and Africa.¹⁷ We calculate the emissions and use of backstop energy as a percentage of GDP, and look at the differences in our three country groups between aggregated consumption (aC) results, aggregated utility (aU) and aggregated utility with Negishi weights (aUN).

In general we observe that the group of High developed countries will be required to undertake stronger efforts toward climate policy based on the aggregated utility social welfare function and compared to both the aggregated utility function with Negishi weights and the aggregated consumption function. Differences between optimal climate policies are smaller for Developed countries. The group of Less developed countries will not need to undertake as much climate action in the aggregated utility case than in both other cases. This result is obviously driven by the differences in marginal utility in the aggregated utility case and one could argue that climate policy is only used as a means of wealth transfer. Nevertheless, this is not entirely true, since one can also observe differences in the aggregated utility case with Negishi weights as well as the aggregated consumption case, which should not exist if income differences were the only reason for the differences in climate policy. Hence, one should be able to allocate some of the differences in climate policies to the differences in the effectiveness of regional climate policies.

¹⁷These definitions were chosen solely for the presentation of the results and the (qualitative) similarity of their climate policies.

Figure 2: Comparisons of climate policy (modified Rice-99 model)



3.2 Criteria for aggregation

The previous analysis should have made it clear that the way a policy maker chooses the unit of aggregation in the social welfare function may induce optimal decisions that range from anything like inaction to the highest feasible effort.¹⁸ However, the theoretical results above do not show that one modeling approach is necessarily better than another. Instead, the theoretical results only suggest that there may be significant differences in the climate policies depending on how one aggregates units. The question that obviously now arises is as whether or not it may be possible to come up with criteria that tell us under which circumstances it may be preferable to follow a more aggregated consumption approach, and in which cases it may be better to rely on a social welfare function that aggregates individual utility. This certainly depends on a multitude of additional criteria. This section will introduce both potential positive and normative criteria that a policy maker may wish to use in order to help place priority on the one or the other aggregation level.

3.2.1 Positive criteria

Positive criteria are those based on facts and can, therefore, be verified to some extent. The intention here is to look more deeply into which positive criteria we may use in order to place

¹⁸In a less extreme view that would come out of a more general model allowing further trade-offs, we should still expect to find that the aggregated utility model leads to more mitigation effort than the aggregated consumption model. See also the empirical section above.

more preference on a more aggregated social welfare function, or on one that take more strongly each individual's utility into account.

One of the points raised already above is that agents, or units, must be similar enough in order to make aggregation meaningful. As a consequence, discussion should not be on the optimal size of sub-groups, but on the **degree of similarity** between its members. Thus, if we look at countries like Luxembourg or Liechtenstein, then climate change is likely to impact these small countries uniformly enough to induce insignificant differences to the climate actions of the agents even if we were to split both countries further, into e.g. North and South Luxembourg. Thus, aggregation at this national level for these countries may make sense. However, take Russia, the USA, or Africa. These three are modeled as being each one regions in most integrated assessment models, yet the climate impacts vary vastly even within their respective regions. As noted for example above, climatic changes may have both positive and negative impact on different parts of Africa (Parry et al. (2007)). Based on this, it may be necessary to model additional sub-regions in order to minimize issues related to the Aggregation Dilemma.

However, there may be political circumstances that would allow for an aggregation of a region despite significantly different climate impacts across its agents. This would be the case if the agents within a region act cooperatively, and consequently if there is room for transfers to those agents that are most strongly impacted by climatic changes. If one wants to aggregate heterogeneous agents into one region, then has to have knowledge of the **institutional characteristics**, namely the potential for coordinated efforts and cooperation. Thus, here the implicit assumption would be that a kind of Kaldor-Hicks compensation should be applied within aggregated regions.¹⁹ Nevertheless, we know that coordination failures certainly arise at the world level, but very often even at the regional one, e.g. in Africa. We not only know this from theoretical works on coalition formation (Ray and Vohra 1999), but also from coalition formation studies in the climate change literature (Heal 1994, Carraro et al. 2006, Bréchet et al. 2011, Bréchet and Eyckmans 2012). Obviously, the policy side has also seen little agreement at the world level and conflicting views at regional levels, with most international climate conferences ending up without a full consensus (Van Alstine et al. 2013). Thus, modeling climate policy while aggregating heterogeneous agents into one region will certainly be anything from misleading to wrong if coordination failures or non-cooperative behaviors are the norm rather than the exception.

While one may ideally wish to study heterogeneous agents at the smallest level, thus in the aggregated utility model, it may be infeasible due to **data constraints** and **complexity**. Data constraints are certainly one main reason for which it is difficult to look at individual agents, or

¹⁹Sandmo (2007) and Anthoff (2011) show that if no lump-sum transfers are allowed between countries then this will increase optimal climate action for the wealthy.

very small units/regions (Orcutt et al. 1968). There is ample measurement error out there, and often it is easier to predict the behavior of the aggregate than an individual. In addition, increasing complexity may itself lead to infeasible optimization problems, both in terms of time constraints and solvability. Another issue has been raised by Nordhaus and Sztorc (2013), who noted that an increasingly complex code for the simulation exercises that lead to the policy recommendations is much more likely to be error prone. The authors note that “[a] rule of thumb is that well-developed software contains in the order of 1 error per source line of code (SLOC). Since many computerized climate and integrated assessment models contain between 10,000 and 1 million SLOC, there is the prospect of many bugs contained in our code.” Consequently, the more disaggregated an integrated assessment model, the more likely it will contain erroneous code. This is yet another issue that needs to be carefully weighed against increasing the number of groups or regions in the model.

3.2.2 Normative criteria

In contrast to positive criteria, normative ones are value-based and cannot be verified against real data. Hence, any use of normative criteria involves a value judgment which is opinion-based.

When it comes to normative criteria, the main question really is as to who should count for a social welfare function? And should a single unit or a small region that may be very strongly impacted by climate change be allowed to ‘dominate’ the climate action of the rest of the world? As Blundell and Stoker (2005) note, “[t]o assert that there is a ‘correct’ individual level at which to apply a mathematical model that is in line with rational behavior is to take a stand on those issues.” And taking a stand on these issues requires to accept the one or the other normative perspective which, depending on the point of view, may lead to drastically different results.²⁰

Let us take the assumption that **each individual counts** towards welfare. In this case we have to rely on a Samuelson-Bergson welfare function, which would be best represented by the aggregate utility function. Again, if individuals are sufficiently similar, then also the results from the aggregate utility function will likely be sufficiently close to those from the aggregate consumption function, or one based on any intermediate level of aggregation. However, and this is proven above, if the individual agents are sufficiently different, then the results cannot be expected to be consistent.

²⁰Take, for example, a brown politician who, simply due to some given prior, holds an aversion to any climate action. Then it should be clear from the analysis above that the brown politician would prefer to follow benefit-cost advices that are given based on the aggregated consumption model. In contrast, take a green politician who believes climate change is relevant and one should do the maximum to avoid it. In this case society may be suggested to follow those climate policies that come out of the aggregated utility model.

The question is, though, as to what happens if one agent is so strongly negatively affected that his deprivation completely drives climate policy? Obviously, we could assume that there are transfers to this individual that may deal with this situation.²¹ However, we may not be able to fully understand how our climate policy result comes about since the integrated assessment models tend to be partially black boxes, in the sense that one throws in some numbers, some magic occurs, and one gets out some numbers which then lead to a climate policy advice. Thus, we may only see that the aggregated utility model suggests ‘excessive’ climate policy, which Fleurbaey and Tungodden (2010) dub the **tyranny of non-aggregation**. There are ways of dealing with this issue, but they require a re-formulation of the social welfare criteria that one uses.

However, if one wants to avoid the tyranny of non-aggregation through relying on the aggregated consumption model à la DICE, then one may give rise to a similar problem, namely the **tyranny of aggregation**. In this case it may be the case that a small benefit arising due to climate inactivity of the many may be optimal despite this leading to a strong climate impact on a few. Again it may be necessary to rely on a different a social welfare function. However, as Fleurbaey and Tungodden (2010) note, “all criteria avoiding the two tyrannies must necessarily violate such basic conditions as the Pigou-Dalton principle of transfers or replication invariance.”

4 Conclusion

In this article we have shown that the level of aggregation at which one evaluates a social welfare function in integrated assessment models may have a significant impact on optimal climate action. In particular, regionally-disaggregated climate models should prescribe stronger climate policies than aggregated models. This result relies on two mild and widely-accepted assumptions, namely asymmetric climate change impacts and declining marginal utility. We show how, in theory, an aggregated utility model can easily generate infinite willingness to undertake mitigation efforts, while its aggregated consumption counterpart may prescribe limited or even zero climate action. This we call the Aggregation Dilemma, and we show how it dwarfs most other policy-relevant aspects in the climate change cost-benefit analysis. Though the policy recommendations from fully aggregated models like the DICE model are always used as a benchmark for policy making, the results here suggest that this should be done with the reservations raised by the Aggregation Dilemma in mind.

We then provide empirically-relevant estimates of the Aggregation Dilemma using a marginally

²¹I cannot avoid to throw in a note on the Negishi weights here: These weights would even worsen this normative situation, in the sense that the deprived individual will receive such a low welfare weight that his situation may not affect climate policy, yet still keep him poor.

modified RICE-99 model. Estimates of the potential errors of aggregation suggest that a higher level of aggregation leads to a much lower climate policy, with total world emissions in the aggregated consumption model being up to 26% higher than in the aggregated utility model. Furthermore, the policy maker would use no backstop energy if he were to rely on the aggregated consumption model for policy evaluation. This stands in contrast to his use of backstop energy in the aggregated utility model, where the model optimally allocates a maximum of 1.2% of the Gross World Product to the backstop use. In general we observe that richer countries will be required to undertake stronger efforts toward climate policy based on the aggregated utility social welfare function and compared to both the aggregated utility function with Negishi weights and the aggregated consumption function.

We also propose both positive and normative criteria that may aid in deciding on the level of aggregation one might wish to choose. These criteria depend, among others, on data feasibility, assumptions about political constraints (e.g. intra-regional transfers), and axioms that one may feel a social welfare function needs to fulfill. The final choice of the level of aggregation at which one models decisions concerning climate policy should, certainly, take these criteria into account. Yet, at the same time, one must not neglect the basic theoretical results presented above, and that is if one were to model climate policy at the smallest unit of aggregation, then the willingness to undertake climate action is potentially very large, and certainly much larger than at any level of aggregation.

Further questions arising from this work are obvious. One, is it possible to study, within a most highly disaggregated model, the true costs of climate change? One may certainly only obtain a benchmark from this analysis, as impacts like conflicts, diseases or financial and natural disasters can easily re-shape the course of a county, country or region. However, all other estimates of the costs of climate change may rest on levels of aggregation which simply average the true costs away.

Secondly, it is of clear importance to obtain more knowledge about the local impacts of climate change. While the IPCC does provide regional estimates of climatic changes and potential losses to agricultural productivity, landmass or similar, we have, as of now, still somewhat unlimited knowledge of the actual economic costs involved.

Thirdly, in terms of responsibility and justice, many more questions open up that need to be treated. For example, if it is cheaper for agents to migrate than for the rest of the world to undertake climate policy, then how should one value this forced migration? It is, for example, already well-known that climatic changes led to migration in regions like sub-Saharan Africa, and that we are likely to see increasing migration in the future (Marchiori et al. 2012). We also

discussed above that transfers may reduce the willingness to undertake climate action. However, if we are certain that a reduction in emissions today may reduce climate damages in the future, can we then trade this certainty for the risk that our future generations may not feel it is necessary to transfer funds to those most strongly impacted by climate change? How is a potential change in political or regional boundaries likely to affect this trade-off? These and other questions follow directly from the study above and should be addressed next.

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