The Aggregation Dilemma in Climate Change Policy Evaluation

Ingmar Schumacher*

IPAG Business School

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*IPAG Business School, 184 boulevard Saint-Germain, 75006 Paris, France. Tel.: +352 621264575. E-mail: ingmar.schumacher@ipag.fr
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Abstract

We show that a policy maker who ignores regional data and instead relies on aggregated integrated assessment models is likely underestimating the carbon price and thus the required climate policy. Based on a simple theoretical model we give conditions under which the Aggregation Dilemma is expected to play a role in climate change cost-benefit analysis. We then study the importance of the Aggregation Dilemma with the integrated assessment model RICE (Nordhaus and Boyer 2000). Aggregating all regions of the RICE-99 model into one region yields a 40% lower social cost of carbon than the RICE model itself predicts. Based on extrapolating the results a country-level integrated assessment model would give a more than eight times higher social cost of carbon compared to a fully aggregated model. We suggest that these tentative results require researchers to re-think the aggregation level used in integrated assessment models and to develop models at much lower levels of aggregation than currently available.

Keywords: Aggregation Dilemma; aggregation; Integrated Assessment Models; climate policy.

JEL classification: Q54; Q58

1 Introduction

In this article we take a step towards answering the following question: Assume we had sufficient data and information on regional or country-specific feedbacks between economic factors, actors and climate change. In this case, what would be the cost of ignoring this information and instead of using regional or country-level integrated assessment models to rely on an aggregated, global approach? In a similar spirit, should we push the development of disaggregated models or can we, for our policy analyses, continue to rely on their aggregated counterparts? To answer this question we present both a theoretical model and investigate this question within an Integrated Assessment Model. In our theoretical part we use a simple model that helps us in illustrating circumstances under which ignoring the regional data may turn out to lead to crucial differences in optimal policy prescriptions. In the policy part we forward a quantification of the differences in optimal policies using regional and aggregated versions of the RICE model (Nordhaus and Yang 1996). The contribution of this article is to show that ignoring the regional information is by no means an innocent choice and can lead to substantial divergences in the recommended climate change policies. In this regards, one of our key findings is that the social cost of carbon is on average 40% lower in a world aggregated model (like the DICE model) compared to disaggregated models (like RICE), provided they are calibrated the same. Our findings suggest that a country-level model would predict a roughly eight times higher social cost of carbon compared to a fully aggregated model like the DICE model.

It is clear that we prefer to rely on highly aggregated models for a variety of reasons. While one may ideally wish to study heterogeneous agents at the smallest level, it may be infeasible due to data constraints (Orcutt et al. 1968) and complexity. 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 disaggregated integrated assessment models is much more likely to be error prone. Nevertheless, in this article we demonstrate that we have to be aware of the negative side effects of this aggregation, and these tend to matter more the larger the regional differences in the climate change impacts. We call this the 'Aggregation Dilemma'. Though the policy recommendations from fully aggregated models like the DICE model (Nordhaus 1993, Nordhaus and Sztorc 2013) tend to be widely 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.

The main assumptions underlying the results in this article are that climate change affects 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], or potentially further levels of disaggregation, lead to different results. In addition, if the results are different, then the question is as to how quantitatively important are those differences. In case we find significant differences in optimal policies between aggregated and disaggregated models, then we have to ask ourselves whether the benefits of using a more aggregated model (e.g. simplicity and data availability) necessarily outweigh the costs (e.g. underestimation of carbon prices).

There are other studies that have looked more specifically at different aspects of 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 interac-

[1]Other 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).

[2]Other 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 Teisberg 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).

tion between transfers and climate policy (Sandmo 2006, Anthoff 2011). An excellent overview can also be found in Botzen and van den Bergh (2014). Furthermore, in a series of articles Llavador, Roemer and Silvestre (2010, 2011a, 2011b, 2012) have shown the wide-ranging policy implications of moving away from the discounted utilitarian criterion towards more inclusive criteria of welfare or more egalitarian ones. 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 be aware of when evaluating climate policy. Nevertheless, it is important to keep in mind that in this article we only address the Aggregation Dilemma itself, and thus study the impact of ignoring the importance of asymmetries by (falsely) favoring more aggregative models. In this respect, Dennig et al. (2015) have shown that global mitigation efforts will be higher in case the poor are predominantly stronger impacted by climate change. This gets close to our result, namely that one should not ignore regional income and climate impact differences when calculating carbon prices, since otherwise one would significantly underestimate the necessary mitigation effort.

An article that raised a somewhat similar point to ours is Hassler and Krusell (2012). In that article, the authors develop a four region integrated assessment model and show that the optimal policy in a homogenous region world differs from the optimal policy in a heterogeneous region world from the individual perspective of a region. Thus, the authors look at a decentralized setting and study the result of regional heterogeneity, while we look at a global policy maker and more carefully investigate the implication of aggregation. Another complementary paper is the econometric study Fezzi and Bateman (2015). In that article the authors show that due to non-linear impacts from climate variables on farmland values more aggregated regressions do not obtain the same results as their disaggregated counterparts.

In this article we do not discuss the large literature on aggregation theorems. Our purpose in this article is not to prove that regional climate change models cannot be potentially characterized by a representative agent of some sort. On the contrary - we do know that we can potentially construct a utility function that will be the aggregated, representative agent equivalence to disaggregated climate models (Acemoglu 2009). However, no integrated assessment model has done so. For example, the (world aggregated) DICE utility function is the same as the (regionally-disaggregated) RICE utility functions. Going further, what would the representative agent utility function in the RICE model look like if we had aggregated the RICE regions from country-level data? These are problems that we have little answer to. Furthermore, the construction of a representative agent requires full use of the disaggregated data. Hence, the original reasons for using aggregative data (data availability/quality, easier to predict average than individual behavior, etc.) do not apply any longer. As a result, researchers may as well simply work with the disaggregated models as they would anyway need the same data if they were to construct an aggregative representative agent model.

The purpose of this article is to show that aggregated Integrated Assessment Models like the DICE model, or the RICE model, in general should not lead to the same optimal climate policy that a regionally-disaggregated version of the same model would advocate. Specifically, we show that aggregated models tend to (significantly) underestimate the social cost of carbon.[3] We believe that if this fact gets acknowledged then this should move the research agenda away from fully aggregated climate change models towards more regional or country-level analyses.

The plan of the paper is the following. In section 2 we discuss a simple analytical example in order to show that only few, well-accepted assumptions are necessary to induce the Aggregation Dilemma. This helps us to point out two main issues: One, the optimal climate policy tends to be smaller in aggregative models compared to disaggregated ones. Two, under realistic assumptions the marginal willingness to undertake climate policy may even be infinite when policy is determined based on a disaggregated model. In contrast, an aggregated model would have a

[3] While the DICE 2013 model estimates a higher optimal carbon price compared to the RICE 2010 model, it must be acknowledged that both cannot be directly compared as they are based on different calibrations. If they were based on the same calibration, as we show for an older RICE version, then the social cost of carbon for the aggregated model should be substantially lower.

bounded marginal willingness to undertake climate action. In section 3 we provide an estimate of the Aggregation Dilemma based on a minimally-modified RICE model. Section 4 concludes with some lessons one may wish to take away from this study.

2 A simple result on the Aggregation Dilemma

In this section we frame the problem at hand within the basic features of the integrated assessment models in order to highlight as to what drives the Aggregation Dilemma. We shall do that in the most simplest setting, and do so simply to illustrate the underlying mechanics of the Aggregation Dilemma. In order to do so, it is useful to frame the problem within the current climate policy debate. The predominant approach is to rely on models that combine 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,[4] 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.

The original DICE model (Nordhaus 1993) and its currently latest version (Nordhaus and Sztorc 2013) are highly aggregated integrated assessment models. There are economic and climatic feedbacks, and a policy maker evaluates the optimal allocations that maximize utility subject to economic and climate feedback constraints. The world is modeled as one unit, with all individual consumption being aggregated, averaged across individuals, and then evaluated in a utility function. 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

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

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 sufficiently similar.[5] We 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'.

Let us assume there exist $N \geq 2$ individuals[6], each having a positive endowment of w/N in period 1 and of $(1+g)w/N$ in period 2. For our purpose it does not matter how many individuals there are. In fact, what we show is that our result does not depend on the number of individuals, but simply arises because we disaggregate the world into e.g. North and South, or into regions, or countries, or individuals. We assume the growth rate g is bounded from below, with $g > -1$, however it is a non-vital component of the model but simplifies the subsequent exposition. In the initial period we assume that climate policy can be undertaken, where each individual may contribute an amount $A_i \in [0, w/N]$, while the second period is the impact period, in which agents potentially benefit from the climate action of the initial period. For simplicity, we shall here assume that all individuals are the same except that they face different impacts from climate change. The assumption that all individuals are the same is certainly not realistic and tilts the model in favor of an aggregative model. Nevertheless, we show that, even in this case, regional differences in climate change impacts are enough to induce substantial differences in optimal policies between disaggregated and aggregated models. Each individual will be affected by climate change, denoted by ψ_i, that reduces the period two growth rate and each individual is

[5]See 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).

[6]When we talk about individuals we have any unit of disaggregation in mind, may it be regions, countries, counties or true individuals. For the sake of simplicity we simply call these different levels of disaggregation 'individuals'.

affected differently. We denote the budget constraints in period one and two respectively by

$$w/N = c_{1i} + A_i, \tag{1}$$

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

which hold $\forall i = 1, ..., N$. We can order individuals and the impact on them according to $\psi_i > 0$, $i = 1, ..., N$, where $\psi_1 < \psi_2 < ... < \psi_N$. Thus, individual 1 will see the weakest impact from climate change[7], while individual N will be impacted the most, given by ψ_N. The average impact is given by $\bar{\psi} = \frac{1}{N}\sum_i \psi_i$.

There is a multitude of empirical evidence that climate impacts will not be uniform across the world but affect regions differently. Most of this evidence on substantial differences in local or regional impacts of climate change has been collected in the contribution of Working Group II of the Fourth Assessment Report of the IPCC, and we refer the reader to Parry et al. (2007) for more details. The results presented in the report 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 realized in 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

[7]One 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 $\psi_i > 0$. For a model where climate policy has more the character of a transfer the reader is referred to an older working paper version of this article (Schumacher 2014). The difference to that previous model is that, in the current article, mitigation effort is not 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 previous model we were more closely dealing with adaptation efforts.

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.

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 functions ψ_i.

A 1 *Functions* $\psi_i(\sum_i A_i) \in (0, 1+g)$ *follow* $\psi_i(0) > 0$, $\psi_i'(\sum_i A_i) < 0$, $\psi_i''(\sum_i A_i) > 0$ *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, while and the marginal benefit at zero abatement expenditure is finite. This last assumption is not vital but it helps to nicely carve out the point that climate policy may not be undertaken simply because it is extremely useful at the limit, but for the reasons that we shall discuss below.

We will furthermore work with the following assumption.

A 2 $\psi_i'(\sum_i A_i) = \psi_j'(\sum_i A_i)$, $\forall\, i = 1, ..., N$ *and all* $j = 1, ..., N$.

While the previous assumptions should be standard and easily acceptable, Assumption 2 is a strong one. Clearly, it could potentially come from models that predict an equality between marginal abatement benefits and marginal abatement costs, which together with emission trading schemes eventually may induce equal marginal abatement benefits across individuals. Another reason is that it facilitates the comparison between the disaggregated and the aggregated model. However, there is clearly no need to be naïve about this assumption: It is unrealistic and only taken for the purpose of illustrating the potential extent of the Aggregation Dilemma in the most simplest mathematical framework. We provide a discussion of this after Proposition 1. However, especially with the subsequent Assumptions 4 and 5 in mind, it should be obvious that the general message of the Aggregation Dilemma stays unchanged.

We now define the utility function of agents.

A 3 *The utility function of agents takes the form* $u(c_i)$*, with* $u'(0) = \infty$*,* $u'(c) > 0$ *and* $u''(c) < 0$*.*

It is thus a concave function where the Inada condition insures an interior solution in consumption.

Our approach then is as follows. We first introduce the policy maker's maximization problem assuming he has all the necessary data and information about all individuals and makes full use of it. We shall dub this the *Disaggregated Case*. We then introduce the model where the policy maker ignores this information and instead models the world as consisting of only one individual, namely the average individual. This we dub the *Aggregated Case*. Then we compare the different policies that arise from these models. For those readers unfamiliar with aggregated or disaggregated integrated assessment models it must be emphasized that they are much more complicated models that are intended to be policy-relevant and thus sufficiently close representations of reality. We neither claim that our highly stylized model below is policy-relevant in a quantitative sense nor intend our theoretical model to be an approximation to the integrated assessment models. Nevertheless, the basic structures of mainstream integrated assessment models like the RICE and DICE models, in terms of aggregation in e.g. the DICE model, disaggregation in e.g. the RICE model, as well as the possibility to undertake a costly action now that benefits the future, are sufficiently close to these models below so that it makes sense to discuss the Aggregation Dilemma in a qualitative way via this stylized model. In the next section we provide a quantitative estimate of the costs of aggregation.

The **Disaggregated Case** is given by

$$U\left(c_{1i}, ..., c_{1N}, c_{2i}, ..., c_{2N}\right) = \sum_i u(c_{1i}) + \sum_i u(c_{2i}), \tag{3}$$

which should be maximized subject to (1) and (2). As suggested above, assuming all individuals to be identical and having the same incomes with the only differences being individual-specific climate impacts intuitively tilts the model towards favoring an aggregative approach.[8] Consequently, if we observe differences between the aggregated model and this disaggregated one, then one should expect those differences to be even more important in models that take further differences between the individuals into account.

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

$$u'(c_{1i}) \geq -\frac{w}{N} \sum_i u'(c_{2i}) \psi_i'(\sum_i A_i), \tag{4}$$

for all $i = 1, ..., N$, which hold with equality for interior A_i.

The **Aggregated Case** is given by

$$U\left(\sum_i c_{1i}, \sum_i c_{2i} \right) = N u\left(\frac{\sum_i c_{1i}}{N} \right) + N u\left(\frac{\sum_i c_{2i}}{N} \right), \tag{5}$$

which should be maximized subject to equations (1) and (2). Thus, the main differences between the Disaggregated Case and the Aggregated Case is that the policy maker ignores regional asymmetries in the Aggregated Case and instead simply averages consumption across all individuals.[9] We shall show that it is precisely this averaging which leads to potentially drastic differences in optimal policies whenever we have differences in the climate impacts on individuals and decreasing marginal utility.

The first-order conditions will be given by

$$u'\left(\frac{\sum_i c_{1i}}{N} \right) \geq -u'\left(\frac{\sum_i c_{2i}}{N} \right) \frac{w}{N} \sum_i \psi_i'(\sum_i A_i), \tag{6}$$

[8] A word on Negishi weights may be in order here since they tend to have an important standing in the integrated assessment literature. The equality of all functions but especially income can also be interpreted as implying that Negishi weights have been put in place. Hence, a policy would not be undertaken to equalize incomes across regions, e.g. in the form of wealth transfers, but solely in the interest of choosing the optimal climate policy.

[9] An alert reader may want to point out that the constraints (1) and (2) are not properly averaged yet. However, it can easily be shown that this model is fully equivalent to one where both constraints are evaluated at the averages. This was not done to minimize notation.

for all $i = 1, ..., N$, which hold with equality for interior A_i.

If we now compare the two sets of first-order conditions from the Aggregated (eq. (6)) and from the Disaggregated Case (eq. (4)), then the main difference comes from the fact that in the Aggregated Case we have only the second-period marginal utility of aggregated consumption, while in the Disaggregated Case we have the *sum* of all individual's second-period marginal utilities. We state the first result of this theoretical part in the following proposition.

Proposition 1 *Let $\tilde{A}$ and $\tilde{c}$ denote the optimal expenditure on respectively mitigation and consumption in the Aggregated Case, while $\hat{A}$ and $\hat{c}$ refer to the ones in the Disaggregated Case. Then under Assumption 1 and 2 we find that*

$$\sum_i \tilde{A}_i < \sum_i \hat{A}_i.$$

Proof of Proposition 1 *Proof by contradiction. From the first-order conditions of the aggregated utility model we have $u'(c^d_{1i}) = u'(c^d_{1j})$, $\forall i, j$. Assume $\sum_i \tilde{A}_i = \sum_i \hat{A}_i$. This would imply*

$$u'\left(\frac{\sum_i \tilde{c}_{2i}}{N}\right)\frac{w}{N}\sum_i \psi_i'(\sum_i A_i) = \frac{w}{N}\sum_i u'(\hat{c}_{2i})\psi_i'(\sum_i A_i).$$

Simplifying gives

$$Nu'\left(\frac{\sum_i \tilde{c}_{2i}}{N}\right) = \sum_i u'(\hat{c}_{2i}).$$

However, since $u'(c)$ is a convex function then by Jensen's inequality the equality above is impossible. Instead, we know that for $\sum_i \tilde{A}_i = \sum_i \hat{A}_i$ we obtain $Nu'\left(\frac{\sum_i \tilde{c}_{2i}}{N}\right) < \sum_i u'(\hat{c}_{2i})$, which implies that $\sum_i \tilde{A}_i < \sum_i \hat{A}_i$.■

What Proposition 1 shows it that, despite everything else being equal, mitigation actions in the Disaggregated Case will be larger than in the Aggregated Case as long as we have declining marginal utilities, asymmetric climate impacts, and A2 holds. If we assume declining marginal utilities away, then both the Aggregated and Disaggregated Cases lead to equivalent results. Nevertheless, the declining marginal utility is certainly one assumption that protrudes through the whole economic literature.

We argued above that A2 is a strong assumption. Yet it is not unreasonable to assume that, in the medium run, the marginal abatement benefits will converge. As more and more carbon markets are being opened and interlinked, as more and more low hanging fruits are getting fished out of the pond, and as technologies spread more and more across the globe, it is highly likely that a convergence of marginal abatement costs also leads to a convergence of marginal abatement benefits (assuming sufficiently efficient markets).

Nevertheless, assuming the unlikely scenario that Assumption A2 will not be satisfied even in the medium run, then it is illuminating to see the implication of relaxing this assumption. Intuitively, we would expect then there to be specific cases under which Proposition 1 does not hold. We show this via a two region case now, denoting the two regions as i and j. In this case equations (4) and (6) can be re-written as

$$u'(c_{1i}) \geq -\frac{w}{2}\Big(u'(c_{2i})\psi_i'(A_i + A_j) + u'(c_{2j})\psi_j'(A_i + A_j)\Big), \tag{7}$$

and

$$u'\left(\frac{c_{1i} + c_{1j}}{2}\right) \geq -u'\left(\frac{c_{2i} + c_{2j}}{2}\right)\frac{w}{2}\Big(\psi_i'(A_i + A_j) + \psi_j'(A_i + A_j)\Big). \tag{8}$$

Now let us look at two possible cases. The first one is $\psi_i > \psi_j$ together with $\psi_i' > \psi_j'$. This is the case of region i being more strongly impacted by climate changes, and also its marginal abatement benefits are higher than those of region j. We would expect region i to correspond, for example, to the South, which is expected to be hit harder by climate change but which also tends to have higher marginal abatement benefits than the North, here region j. In this case, both $u'(c_{2i}) > u'(c_{2j})$ and $\psi_i'(A_i + A_j) > \psi_j'(A_i + A_j)$, and thus our previous result in Proposition 1 is reinforced.

Instead, assume now that $\psi_i > \psi_j$ together with $\psi_i' < \psi_j'$, and let us take, for illustrative purposes, the extreme case where $\psi_i' \to 0$. In this case find that it is possible that abatement in the aggregated case is larger compared to the disaggregated one. The reason is that abatement is not useful for the region i which is subject to stronger damages, and thus in the disaggregated case the marginal abatement benefit is weighted by region j's marginal utility only, while in the aggregated case utility is a weighted average of both regions' consumption levels. As a result, second period's marginal utility in the aggregate case is larger than in the disaggregated one, and consequently more abatement will be undertaken in the aggregated case.

One may wish to emphasize that these results may be weakened or strengthened depending on what additional differences between individuals are imposed. For example, empirically speaking we know that there are differences in income between regions, the growth rate tends to be larger for poorer regions, utility functions may differ, technology levels, and so on. It goes without saying that all these points will have an impact on the total mitigation efforts of the disaggregated and aggregated case. Thus, it is necessary to evaluate how relevant the difference between these cases really is. Before we tend to this in the next section, we will push the theoretical results on the Aggregation Dilemma somewhat further in order to show issues that are similar to those raised by the Dismal Theorem (Weitzman 2014).

2.1 Two extreme cases

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

A 4 *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.[10]

A 5 *Assume that* $\exists h \in \mathbb{Z}(N)$, *s.th.* $\forall\, i \geq h$, $\psi_i(\sum_i w_i/N) \geq 1 + g$.

[10] We took some mathematical liberties as this would make income negative. To be precise, for this assumption and the next, we assume $c_{2i} = \max\{0, (1 + g - \psi_i)w/N\}$.

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 A4 and A5 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* A4 *implies that the marginal benefit to mitigation expenditure is*

$$\lim_{\sum_i A_i \to 0} \sum_i u'(c_{2i})\psi_i'(\sum_i A_i) = \infty,$$

while

$$\lim_{\sum_i A_i \to 0} u'\left(\frac{\sum_i c_{2i}}{N}\right) \sum_i \psi_i'(\sum_i A_i) < \infty.$$

Assuming A5 implies that

$$\forall A_i \in [0, w), \sum_i u'(c_{2i})\psi_i'(\sum_i A_i) = \infty,$$

while

$$\forall A_i \in [0, w), u'\left(\frac{\sum_i c_{2i}}{N}\right) \sum_i \psi_i'(\sum_i A_i) < \infty.$$

Proof of Proposition 2 *Follows directly from A4 and A5.* ■

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 Disaggregated Case to infinity. In contrast, in the Aggregated Case, this does not happen since climate impacts get averaged away.

Furthermore, assume there exists at least one agent who is so strongly impacted by climate change that he would lose everything even if all agents were to spend all income on mitigation effort. As a result, the willingness to undertake climate action would be infinite at every level of mitigation expenditure. This last result seems controversial in the sense that transfers could eliminate it. Allowing for transfers in a regional public good model, Sandmo (2006) and Anthoff (2011) have shown that this may reduce climate action. For example, if A5 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 maximal climate action again.

The key point, in any case, is not that there may exist a policy like adaptation, mitigation or transfers, that may reduce the social cost of carbon and thus the willingness to undertake climate action. Instead, the key point is that aggregation matters when units are subject to asymmetric climate change and that disaggregating then tends to increase the social cost of carbon.

3 The Aggregation Dilemma in the RICE model

As suggested above, the mathematical result suggests that under mild assumptions, the Disaggregated Case may potentially lead to an infinite marginal willingness to undertake climate policy. This stands in stark contrast to the Aggregated Case, which may, under the same assumption, recommend no climate action at all. Hence, the policy implications of the Aggregation Dilemma may be substantial. It is, thus, certainly of interest to investigate the relevance of the theoretical result and to investigate as to how important this result may be in the hypothetical world of integrated assessment modelling. Clearly, if this turns out to be sizable, it is reasonable to believe that aggregated integrated assessment models (like the DICE model) may prescribe a far too lenient climate policy than would be necessary. In order to provide a policy-relevant estimate of the Aggregation Dilemma, we minimally adapt the code for the RICE-99 model that Professor Nordhaus kindly provides (Nordhaus and Boyer 2000).

First off, 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 the sake of argument we shall simply suggest that we have good data and information about the regions of the world as defined in the RICE model, and take this as our starting point.

We study three different scenarios. The first scenario is based upon the Disaggregated Case, which is defined as

$$U^r = \sum_T \sum_N 10 * R(T)P(T,N) \log\left(\frac{C(T,N)}{P(T,N)}\right). \tag{9}$$

Utility U^r 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 Disaggregated Case as defined in the theoretical part above, and furthermore we want to avoid the ethical connotation underlying Negishi weights.[11] 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 Disaggregated Case and the Aggregated Case. Thus, we also study the potential differences that may arise through the use of Negishi weights. Our second scenarios is therefore defined by

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

where U^{rN} stands for the utility functional in the Disaggregated Case with Negishi weights ($W(N)$), and it corresponds fully to the social welfare function used in the RICE-99 model. Negishi weights are used to stop incentives for income re-distribution due to initial wealth differences and thereby instead help to focus the policy maker's attention on taking care of the climate

[11]For discussions on the Negishi weights the reader is referred to Stanton (2011).

externality. Thus, if there are differences in the optimal climate policy between the unweighted and the Negishi weighted simulation results, then these should be due to climate policy being used as a means of reducing income differences in the unweighted Disaggregated Case.

The third scenario is the Aggregated Case. For this we aggregate consumption in utility and then average it across individuals, just like in the original DICE model. Hence, we denote the Aggregated Case as

$$U^d = \sum_T 10 * R(T)P(T) \log \left(\sum_N \frac{C(T,N)}{P(T)} \right). \tag{11}$$

One issue here is that this does not yet correspond to a fully aggregated model since the production functions differ across regions. Thus, a policy maker may wish to invest more or less in climate policy depending on how this affects the production functions. Hence, in our final scenario we take the Aggregated Case but, in addition, we aggregate and average the production functions, capital and labor across regions. In the RICE-99 model the production functions $F_i(\cdot)$ are region-specific, depend on total factor productivity A_{iT}, capital K_{iT}, labor L_{iT}, carbon input E_{iT}, the use of backstop energy B_{iT} and are reduced by a climate impact feedback that depends on the level of temperature TEMP_T. Thus, they are given by

$$F_{iT}(K_{iT}, L_{iT}, E_{iT}, B_{iT}, \text{TEMP}_T) = \frac{A_{iT} K_{iT}^{\gamma} L_{iT}^{1-\gamma-\alpha_{iT}} (E_{iT} + B_{iT})^{\alpha_{iT}} - p_{iT} E_{iT} - q_i B_{iT}}{1 + \mu_i \text{TEMP}_T + \nu_i \text{TEMP}_T^2} \tag{12}$$

We then define the aggregate, average production function by aggregating and averaging across regions, such that for all region-specific parameters $x_{iT} = \{A_{iT}, K_{iT}, L_{iT}, E_{iT}, B_{iT}, \alpha_{iT}, p_{iT}, q_i, \mu_i, \nu_i\}$ we define the regional average as $\bar{x}_T = \frac{1}{N} \sum_i^N x_{iT}$. Consequently, a policy maker who ignores region-specific differences thus averages across regions and then aggregates production, such that total world production will be given by NF_T, where the inputs and parameters in this production function are the world averages. Our four scenarios are then summarized as follows.

We present the simulations based on a policy maker's perspective who searches for the opti-

Model	Utility	Production
Disaggregated	U^r	F_{iT}
Disaggregated-N	U^{rN}	F_{iT}
Aggregated	U^d	F_{iT}
Aggregated-A	U^d	F_T

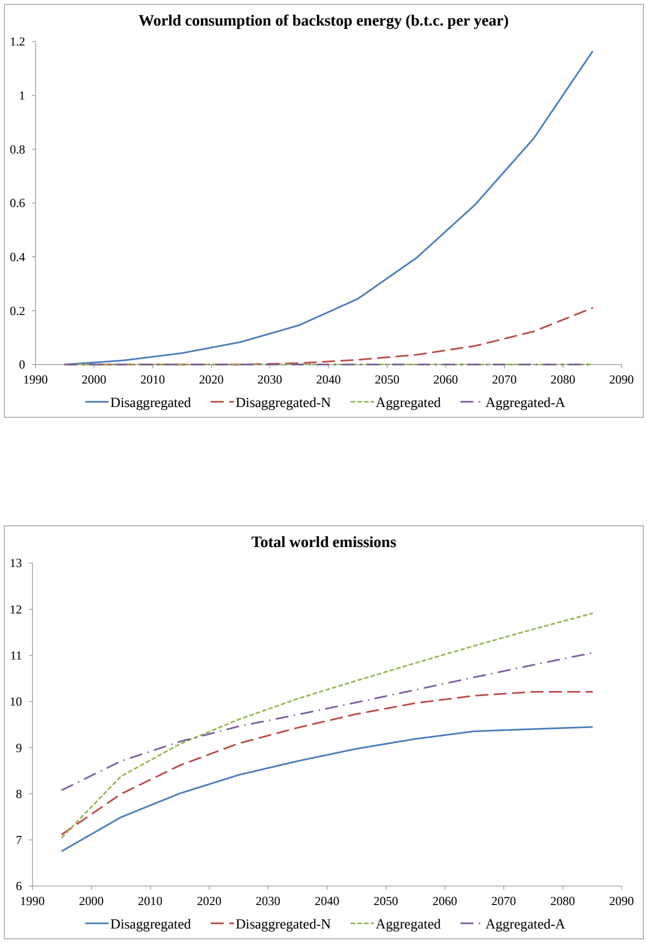
mal solution with the choice variables in this model being region-specific carbon emissions, the use of backstop energy, and per capita consumption. The simulation results are given in Figure 1.[12]

In the Aggregated Case, total world emissions are up to 26% higher than in the Disaggregated Case, and up to 16% higher compared to the Disaggregated-N Case. Aggregating fully, and thus not only ignoring regional differences in consumption but also in production, leads to emissions in the Aggregated-A Case which are initially much larger (20%) compared to the Disaggregated Case (and 13% in the Disaggregated-N Case), with a difference that decreases slightly towards the middle of the century and then increases again. Overall, the stock of CO_2 is initially the largest in the Aggregated-A Case, then it is overtaken after roughly 60 years by the atmospheric CO_2 of the Aggregated Case. Nevertheless, both levels of CO_2 are always optimally higher in the aggregated cases than in the disaggregated ones, with the Disaggregated Case having the lowest level. One reason for the eventually lower emissions in the fully aggregated Aggregated-A Case compared to the utility-aggregated Aggregated Case is that the initially very high emissions in the Aggregated-A Case may already be leading to forced emission reductions after 30 years.

Furthermore, the policy maker would use no backstop energy if he were to rely on either the Aggregated Case or the Aggregated-A Case for policy evaluation. Consequently, even in these fully calibrated models, the aggregated integrated assessment models average the climate damages away and lead to the least climate action. This stands in contrast to a policy maker's use

[12]In fact, the results in the latest version of Nordhaus' RICE model (Nordhaus 2010) conform very closely to ours' (the Disaggregated-N Case). The only difference in the optimal path of CO_2 emissions is that in the new version the emissions increase slightly faster and consequently reduce slightly quicker than our Disaggregated-N case, which itself is equivalent to the model in Nordhaus and Boyer (2000). The reason why we did not use the latest RICE version is because it has not yet been provided in GAMS code.

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



of backstop energy in both the Disaggregated and the Disaggregated-N Case, 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 Disaggregated Case, the total amount of backstop energy used is roughly 7.5 times larger than in the Disaggregated-N Case, the one with Negishi weights. Overall, the Negishi weights tip the scale towards to 'needs' of the richer regions, in the sense that they reduce the incentives for capital transfers from the rich to the poor. Conclusively, whatever one believes to be the correctly-specified regional model, i.e. the one with or the one without Negishi weights, in both cases the results clearly show that ignoring regional differences leads to substantial changes in the prescribed optimal climate policy.

One of the key discussions in the climate policy concerns the social cost of carbon. With this in mind we investigated how the optimal carbon price is affected by varying the level of aggregation. We started off with the level of disaggregation as in the original RICE model, and then, one region at a time, aggregated the utility function until we ended up with one region alone. The results, averaged across 10 different ways of (randomly) aggregating, are depicted in Figure 2, where the x-axis depicts the number of regions, and the y-axis depicts the social cost of carbon relative to the fully disaggregated model. We see that the social cost of carbon in aggregative models is 40% lower than in disaggregated models and that disaggregating by one further unit increases the carbon price by on average 3.75%. Extrapolating this result linearly, we find that the social cost of carbon in a country-level integrated assessment model should be around 8.275 times higher than in a fully aggregated integrated assessment model. In a recent paper Nordhaus (2017) uses the DICE model to estimate the 2015 social cost of carbon to be around $31 per ton of CO2 in 2010 USD. Based on our results we find that an equivalently calibrated model, disaggregated at the RICE level, would yield a social cost of carbon of $\$31 \cdot 1.4 = \$43.4$, while a country-level model would yield a social cost of carbon equal to $\$31 \cdot (1 + 0.0375 * 194) = \$256.53$. We can, therefore, conclude that a policy maker who ignores regional data tends to underestimate the carbon price and thus the necessary policy interventions.

Sensitivity analysis of these results, available from the author, to generally discussed parameters in the integrated assessment literature, namely the discount rate and the intertemporal elasticity of substitution, suggests that a higher discount rate reduces the difference in both the total world emissions and the use of the backstop energy between the Aggregated and Disaggregated Case. The Aggregation Dilemma should, therefore, become more important 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 Aggregated Case only marginally, while we observe large

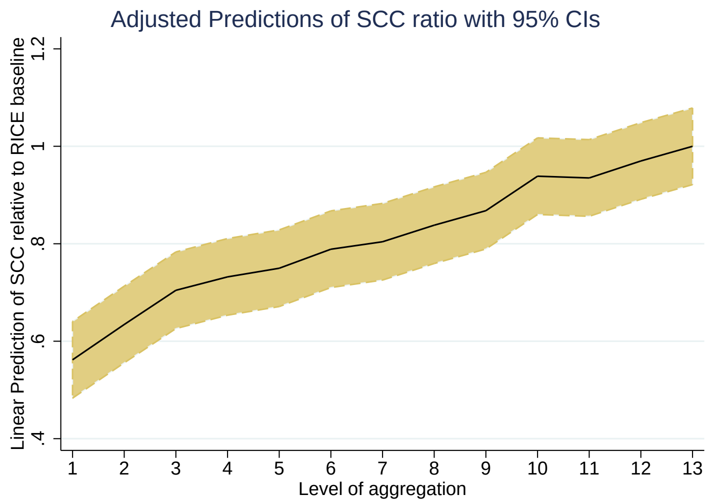


Figure 2: Integrated Assessment results (modified Rice-99 model)
This figure shows the (averaged and smoothed) ratio of the social cost of carbon when moving from the fully disaggregated RICE model to a more highly aggregated counterpart. For example, the fully aggregated model yields a social cost of carbon that is only 60% of the disaggregated RICE model.

changes in the Disaggregated Case. The use of the backstop energy is significantly higher, and total emission are much lower in the Disaggregated Case 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 parameters and the Aggregation Dilemma.

4 Conclusion

In this article we have shown that a policy maker, who - for whatever reason - chooses to ignore regional differences in climate impacts in favor of a more aggregative approach will seriously underestimate the optimal policy interventions. This result relies on two mild and widely-accepted assumptions, namely asymmetric climate change impacts and declining marginal utility. We show how, in theory, a disaggregated model can generate an infinite willingness to undertake mitigation efforts, while its aggregated counterpart may prescribe limited or even zero climate action.

We provide policy-relevant estimates of the Aggregation Dilemma using a marginally modified RICE-99 model. Estimates of the potential errors of aggregation suggest that a higher level of aggregation leads to a much lower investment in climate policy, with total world emissions in the aggregated models being up to 26% higher than in the disaggregated ones. Furthermore, the policy maker would use no backstop energy if he were to rely on the aggregated models for policy evaluation. This stands in contrast to his use of backstop energy in the disaggregated models, where he would optimally allocate a maximum of 1.2% of the Gross World Product to the backstop use. Though the policy recommendations from fully aggregated models like the DICE model tend to be widely 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.

Our results emphasize the need to carefully re-think whether the use of highly aggregated integrated assessment models is appropriate, and thus to re-assess as to what is the correct social welfare function and unit of disaggregation when it comes to estimating the social cost of carbon. Our results here suggest that we should be more careful when aggregating, as aggregation tends to average out differences. Clearly, there are still open questions as to what is the ‘right’ way to aggregate disaggregated units in a social welfare function.

In future research it would be useful to push these results on the Aggregation Dilemma a step further. For example, it would be important to know by how much the Aggregation Dilemma worsens if one moves from the regional RICE model to one with smaller units of analysis, e.g. to country or county levels. In this respect, Krusell and Smith (2009) are currently undertaking a research project with an extremely large number of regions (19,000 in total). In a much less ambitious project we are extending the RICE model to a country-level one. As our results here have shown, since sufficient data on smaller units exists, then given the asymmetric climate impacts across the world it is vital to not neglect this data and fully incorporate the heterogeneities in the integrated assessment modeling so as not to underestimate the true costs of climate impacts across the world.

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