The Comparative Importance for Optimal Climate Policy of Discounting, Inequalities, and Catastrophes

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Abstract

Integrated assessment models (IAMs) of climate and the economy provide estimates of the social cost of carbon (SCC) and inform climate policy. With the NICE model (Dennig et. al. 2015), which is based on Nordhaus's RICE, but also includes inequalities within regions, we investigate the comparative importance of several factors – namely, time preference, inequality aversion, intraregional inequalities in the distribution of both damage and mitigation cost, and damage function. We do so by computing optimal carbon price trajectories that arise from the wide variety of combinations that are possible given the prevailing range of disagreement over each factor. This provides answers to a number of questions, including Thomas Schelling's conjecture that properly accounting for inequalities could lead the inequality aversion parameter to have an effect opposite to what is suggested by the Ramsey Equation.

1. Introduction

Estimates of economic responses to climate change are contingent at times on highly uncertain assumptions, including about the future societies with which climate will interact. Nevertheless, incomplete estimates exist, and when put into integrated assessment models (IAMs), they serve to provide some guidance on the extent of effort society should dedicate to this problem (Stern 2006, Nordhaus 2010, 2013, Tol 1996, 2009).

There are several instances of high mitigation effort recommendations by researchers using these models – most notably the Stern Review, which prescribes a high level of mitigation based on very low discount rates (Stern 2006, Hope 2008, Nordhaus 2007). Other researchers provide a similar sense of urgency based on other features, such as the possibility of catastrophic damages (Weitzman 2012), the possibility that climate damages will disproportionately harm the poor (Dennig et. al. 2015), price effects (Sterner 2008), and damages affecting growth rates (Moore and Diaz 2015).

Here we investigate the interactions between all but the last two of these individually important factors. We also consider one further set of interactions not previously considered – involving inequalities in the distribution of mitigation cost between rich and poor. This provides answers to a number of questions, including the relative importance of inequalities across space vs. across time, and of inequalities vs. catastrophic impacts. Our investigation of these issues is made possible by further development of the NICE model (Dennig et. al. 2015), which is based on Nordhaus's RICE2010 (Nordhaus 2010), but also includes mechanisms to represent inequalities within regions that are not included in RICE or in other existing climate-economy IAMs.

We begin by articulating Thomas Schelling's conjecture that properly accounting for inequalities within generations could lead the inequality aversion parameter to have an effect opposite to what is suggested by the Ramsey Equation (Schelling 1995).[1] We explain how NICE allows us to evaluate this conjecture, and we then show that this *Schelling Reversal* does indeed arise but only under particular conditions. We then show that for most reasonable values taken by the various parameters we consider here, the effect of adding catastrophic damages with certainty at 4°C or 6°C above preindustrial temperatures has a relatively small effect on optimal mitigation when compared with the effect of the other parameters and the effect of including a more fine-grained representation of sub-regional inequalities. Along the way, we display the optimal carbon price trajectories that arise from the wide variety of parameter value combinations that are possible given the primary range of disagreement over the discounting parameters, inequalities in the distribution of both damage and mitigation cost between rich and poor, and a damage function that does or does not assume catastrophic impacts at high global mean temperatures increases.

2. The Schelling Reversal and NICE

In spite of the arguments for urgent mitigation noted in the previous section, there remains a persistent view amongst some economists that there is scant cause for concern. For example, a meta-analysis of the literature on climate damages (Tol 2009) estimates an economic damage of 0.7% of GDP at 2.5°C warming. If this is read against a background of constant growth of GDP at more than 1% per year, it may seem that worrying about the future generations impacted by climate change is not worth the effort – akin to asking Mexico to transfer resources to help a drought-stricken California.

More generally, the growth rate assumed in leading IAMs generates substantial inequalities between generations, as the assumed growth rates and damage functions imply that future generations will grow richer and richer even under business as usual (Dennig et. al. 2015, Anthoff, Tol, Yohe 2009). As a result, the optimal amount of mitigation effort depends very much on two parameters in the social objective of these models: first, the rate at which future generations are discounted simply because they are in the future, which is represented by the *pure time preference* parameter ρ and, second, the relative priority of the poor and the rich, which is represented by the *inequality aversion* parameter η. This latter parameter is also known as the *consumption elasticity of marginal utility*. The rate of pure time preference is the rate at which the weight given to future utility declines with

[1] A related conjecture from Schelling is investigated by Anthoff and Tol 2012 – namely, that the best defense for poor societies against climate change impacts might be to develop quickly, rather than to control greenhouse gas emissions. Our results here shed additional light on this and other important questions framed and partially answered by Anthoff and Tol. Our results here indicate that proper representation of subregional inequalities are crucial to answering such questions – which supports Anthoff and Tol's idea that answering such questions requires taking into account important heterogeneities (pg. 271).

time, and the degree of inequality aversion η represents the diminishing marginal utility of consumption – i.e. the lesser importance of each increment of consumption as one gets richer. These parameters are grounded by some authors on ethical considerations and by others on what are taken to be empirical proxies. But the common result suggested by the Ramsey Equation is that increasing either one of these parameters delays mitigation. That is because the Ramsey Equation states that the discount rate on *damages* (as measured in dollars) is given by

discount rate = $\rho + \eta * g$

where g is the average growth rate of consumption between now and the discounted period. This equation suggests that a greater value for either ρ or η will raise the discount rate on consumption and therefore delay mitigation, given the positive growth rate assumed by these models.[2]

However, if inequalities within generations were taken into account, it is no longer obvious that increasing inequality aversion must have the effect of delaying mitigation that is suggested by the Ramsey Equation and commonly assumed in the literature. In particular, Schelling (1995, p. 400) provocatively noted that "once we disaggregate the world's population by income level, it becomes logically absurd to ignore present needs and concentrate on the later decades of the coming century," but also that mitigation policy amounts to implementing "transfers [that] will be from the currently rich to the descendants of the currently poor, who will, when the benefits begin to be felt, be much less poor than they are now but still poorer than the descendants of the currently rich and probably still significantly poorer than the abatement-financing countries are now" (p. 399). So, on the one hand, properly representing inequalities reinforces the salience of current needs and may recommend a shift of focus from mitigation to adaptation. But the second quote suggests that an important factor that pulls in the opposite direction is the relative wealth of those who pay for the effort and those who benefit from a preserved climate.

Schelling's remarks suggest a pressing question: *in spite of the presumption that future generations will be on average richer than the present generation, could it be true that the more one dislikes inequalities and cares for the disadvantaged, the more mitigation one should want to see*? In other words, *in spite of the fact that aggregate growth together with the Ramsey Equation suggests that increasing inequality aversion would delay mitigation, could it be true that when inequalities are properly accounted for, increasing inequality aversion actually implies faster mitigation?*

In order to evaluate Schelling's conjecture that the answer to these questions might be different than suggested by the Ramsey Equation, as well to answer other pressing questions about climate and inequality, we have developed a modification of the widely used RICE model, which we call NICE (for Nested Inequalities Climate Economy model). As

[2] It is in particular noteworthy that Stern had to choose a low degree of inequality aversion in order to obtain a low discount rate and to recommend an aggressive mitigation policy, whereas Nordhaus adopted a more standard inequality aversion parameter (and higher discount rate) and obtained much more lenient conclusions.

we describe in detail below, NICE incorporates a fuller description of inequalities by income quintile in the distribution of income, damages, and mitigation cost within each global region. Schelling's ideas could be studied with RICE, since inequalities between regions are important and may potentially influence the impact of changing the inequality aversion parameter on the optimal carbon price. However, such inequalities are only one part of the global inequalities within generations, and a fuller study is possible with a more comprehensive depiction of inequalities. With NICE, as explained below, we can actually analyse the possibility of the Schelling Reversal when focusing on inequalities between regions, and identify whether inequalities within regions are a crucial element in the reversal as well.

A description of the model is provided in the online appendix. The main specifications that must be known in order to understand this paper are:

- the social welfare function, a discounted and separable constant elasticity function with population weights:

$$W(c_{ijt}) = \sum_{ijt} \frac{L_{ijt}}{(1+\rho)^t} \frac{c_{ijt}^{1-\eta}}{1-\eta} \quad (1)$$

where W denotes social welfare, L population, c per capita consumption, ρ the rate of pure time preference and η inequality aversion.[3] The subscripts i, j, and t are the region, quintile, and time indices respectively;

- the damage and abatement cost distributions among quintiles, which involve new elasticity parameters ξ and ω such that:

$$d_{ij} = k_{i\xi} q_{ij}^{\xi}; \;\; e_{ij} = k_{i\omega} q_{ij}^{\omega}.$$

For ξ = 1, regional damages are distributed proportional to consumption; for ξ = -1, inversely proportional. For ω = 0, abatement costs fall in equal amounts on rich and poor quintiles; for ω = 2, they fall much more on the rich.

To further illustrate the meaning of ξ and ω, consider an 'economy' comprised of two (equally populous) consumption groups A and B, with A consuming USD 4,000, and B USD 40,000 a year. If this `economy' suffers 5% damage from climate change, they jointly lose USD 2,200. If ξ = 1, A loses 200 and B loses 2,000. If ξ = 0, both A and B lose 1,100. If ξ = -1, A loses 2,000 and B loses 200. B goes from losing 5% to 2.75% to 0.5%, while A goes from losing 5% to 27.5% to 50% of pre-damage consumption. If the same 'economy' experiences a 2.5% abatement cost from climate change mitigation activities, then that total joint cost is USD 1,100. If ω = 0, both A and B pay 550. If ω = 1, A pays 100 and B pays 1,000. If ω = 2, A pays 52.38 and B pays 1047.62. A goes from paying 13.75% to 2.5% to 1.3% and B goes from paying 1.38% to 2.5% to 2.6% of pre-mitigation cost consumption. In this way, the values of ξ and ω affect only the *distribution* of damage and mitigation cost within a region, and not

[3] Ignoring the discount rate, the social objective (1) considers that a population twice as poor as another should receive a greater priority by a factor of 2^η for small increments to consumption (e.g., a value of η = 1 means that providing $1 to the poorer population is as good as providing $2 to the less poor population).

the total amount of regional damage and regional mitigation cost.

The distribution of damages, and thus the value of ξ, depends on where and how the climate changes and modifies the ecosystem at a sub-regional level, on how vulnerable the populations are given the organization of the economy and the infrastructure set-up, and on policy response.[4] The value of ξ has not received much scrutiny so far in the empirical literature, perhaps partly due to the fact that the importance of this parameter has not previously been demonstrated. However, many studies argue that the poor will disproportionately suffer from climate change (Oppenheimer et. al. 2014, Mendelsohn et. al. 2006, 2011, Leichenko and O'Brien 2008, Kates 2000, Cutter et. al. 2003), meaning that ξ is likely to be less than 1, and might even be negative (in particular in the case of health and mortality impacts). We consider that a relevant range for ξ in the present investigation is from -1 to +1.

The distribution of mitigation cost, and thus the value of ω, is even more dependent on policy decisions. Several studies (Bacon et. al. 2010, Daioglou et. al. 2012, Riahi et. al. 2012, Krey 2014) analyse the share of energy in household expenditures and conclude that an increase in energy prices will hit the poor more than proportionally in the absence of compensatory measures, at least in developed nations.[5] This suggests a value of ω less than 1 for a carbon tax alone with no compensatory measures. Several other studies (Cullenward et. al. 2014, Metcalf 2009, Sterner 2012, Williams et. al. 2014, Wilkerson et. al. 2015) agree with the studies just cited, but also conclude that if an increase in energy prices is combined with compensatory measures it need not disproportionately hit the poor, and could even make all but the highest quintile net beneficiaries – for example, if the compensatory measures involve equal per capita redistribution of the revenues from a carbon tax.[6] In light of this, we consider that a relevant range for ω is from 0 to 2, the latter value being obtained when the cost is borne more heavily by the rich.

Another way in which the poor can be spared of some of the mitigation effort is by allowing different carbon prices in the different regions of the world, letting the less developed mitigate to a lesser extent than required under a uniform global carbon tax. In this paper we do not explore this option and leave it for a companion paper in which we compare the relative importance of the within and between-region allocation of the abatement costs.

In recently published work (Dennig et. al. 2015) we show that the value of ξ is of great importance to climate policy. For example, when damages are distributed inversely proportionally to income, optimal mitigation effort under the discounting and inequality aversion assumptions of Nordhaus 2010 is equivalent to optimal mitigation in the more

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[4] Note that the measurement of damages itself has both empirical and ethical dimensions: valuing losses to different parts of the income distribution in the wake of climate change depends both on relatively objective data on property damage, capital losses, etc., and the more ethically challenging questions regarding valuation of loss of life, health, and livelihood.

[5] The papers in Sterner 2012 suggest that even without compensatory measures, a carbon tax in developing nations might not be regressive.

[6] As a consequence, progressive compensatory measures can also arguably improve the political feasibility of carbon taxes, at least as measured by percentage of voters who are net beneficiaries of the policy.

aggregated RICE model under the much lower discounting and inequality aversion assumptions of the Stern Review (Stern 2006). At the same time, when $\xi = \omega = 1$, inequalities within regions are fixed and are not influenced by climate change and abatement efforts. In this case, NICE produces optimal policies which are very close to those found in RICE, enabling us to obtain a good approximation of the results one would obtain with RICE in our analysis. The results of these $\xi = \omega = 1$ model runs show that the mere representation of consumption inequalities within regions does not substantially alter the mitigation recommendations if damages and mitigation cost are proportional to consumption.

NICE reveals the importance of a factor largely ignored by existing IAMs: the interaction between climate change and inequalities within regions and countries. But disaggregating the regions of the world into income strata does not by itself suffice to overturn the usual conclusions. A greater inequality aversion in the social welfare objective pursued by policy may enhance or undermine the recommended level of mitigation depending on the other parameters and assumptions. The evaluation of the Schelling Reversal therefore depends in various (sometimes obvious, sometimes subtle) ways on several conditions. As Schelling argued, the distribution of damages and abatement costs is the essential ingredient in the analysis, and involves both climate, economic, and political assumptions.

3. Results

3.1: The Schelling Reversal and the Interaction between Pure Time Preference and Inequality Aversion, Given Representation of Sub-regional Inequalities

The main innovation in NICE is the more detailed description of intra-generational inequality, and the possible ways in which damages and mitigation costs may affect it. Notice that the specification (1), via the parameter η, picks up on inequality in a similar way, whether it is across time or across space. However, the presence of discounting mutes the effect across time and it is therefore interesting to also vary the value of ρ in the analysis. In our analysis we have examined values between 0 and 3 for the parameter η,[7] and between 0 and 2% for ρ. The interplay between these two parameters, as well as the damage and mitigation cost distribution parameters ξ and ω, determines whether the intergenerational or the intragenerational inequalities dominate, as we show in this section and the next.

In Figure 1 we plot the optimal carbon taxes given the standard damage function (i.e. without the addition of the catastrophic damage term considered below), and retaining a

[7] The value $\eta = 0$ is implicitly applied within countries in the standard analysis that ignores inequalities within countries, but is uncommon in intergenerational analysis. It implies that one is only interested in the total global and intertemporal consumption, and not in its distribution among generations and countries. With our objective (1), consistency of inequality aversion between and within generations and countries is imposed. We provide a fuller discussion of the $\eta = 0$ case in the online appendix, because it vividly reveals the relative sizes of the benefits and costs of mitigation (the former vastly overwhelming the latter, implying very strong mitigation in the optimal policy).

proportional distribution of mitigation costs (ω = 1). The discount rate ρ varies along the columns and the income elasticity of damage ξ varies along the rows. Within each set of axes, we plot five optimal taxes corresponding to different values of the inequality aversion η.

As expected, a reduction in the elasticity ξ has the effect of increasing the mitigation effort, because it hurts the future poor and makes their fate a greater priority for policy.[8] An increase in the rate of pure time preference uniformly decreases the optimal tax, since the benefits of mitigation accrue to the future.

[8] If there were no inequality aversion (η = 0), the value of the income elasticity of damage ξ would not be of any importance, and the mitigation effort would be very high, as we show in Figure A1 of the online appendix.

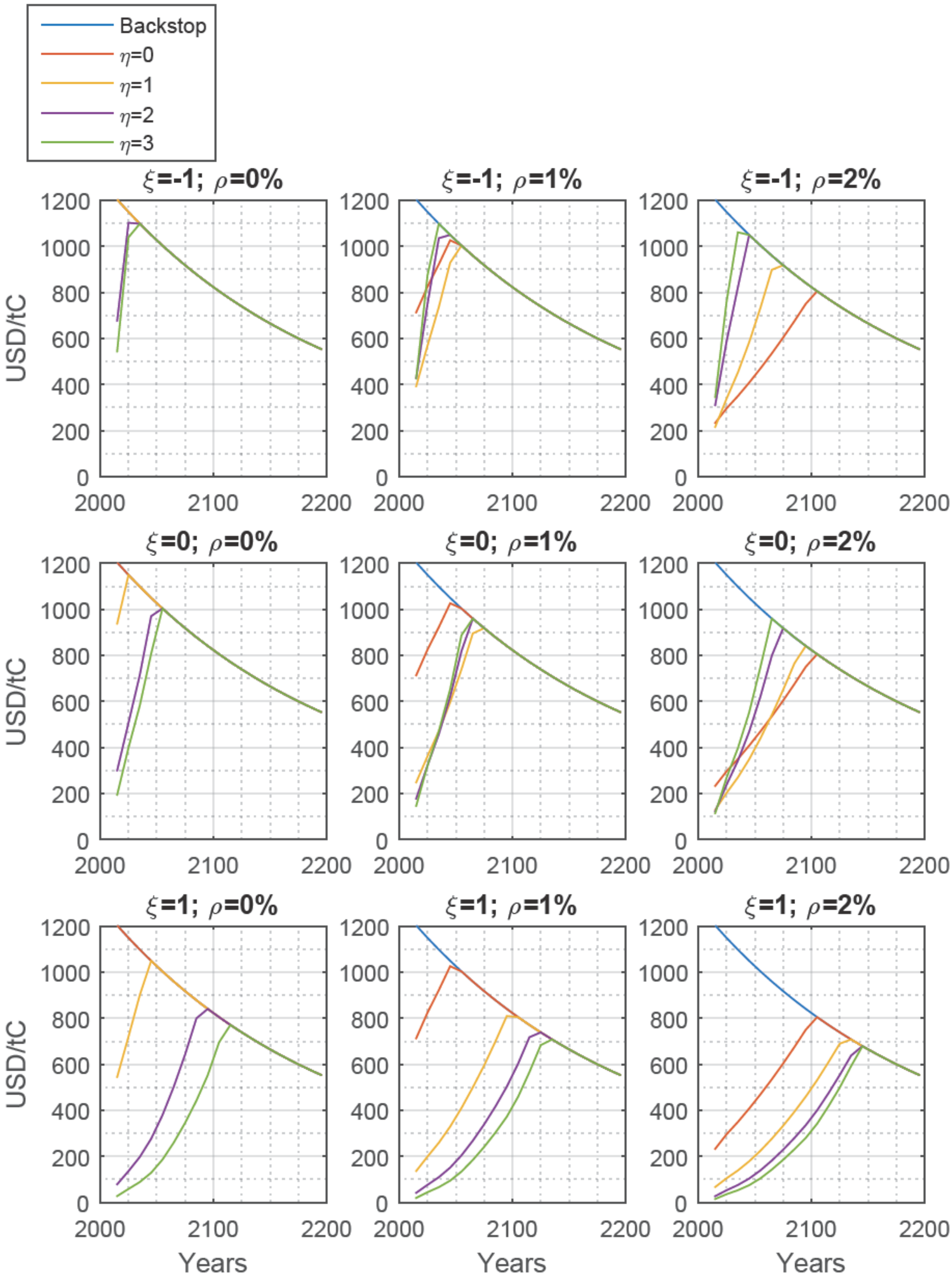

Figure 1: Optimal carbon tax as a function of ρ, η, ξ (with original RICE2010 damages and ω = 1).

In contrast with the parameters ξ and ρ, the role of the inequality aversion parameter η is more ambiguous and complex, illustrating the relevance of Schelling's remarks.

In particular, unlike the rate of pure time preference, an increase in inequality aversion does not necessarily have the effect suggested by the Ramsey Equation. This verifies Schelling's conjecture that a reversal of the effect of inequality aversion is possible once sub-regional inequalities are properly represented.

When damages are not proportional to income and more regressive (ξ = 0 or -1), the effect is reversed, at least for some values of ρ: a higher η leads to a higher tax. This is because in a model with intra-generational distributions of income and damages inequality aversion is doing two things. It discounts future damages relative to current abatement cost, due to the growth in consumption over time (the Ramsey Equation), but it also weighs more heavily damages on the poorer members of society within a generation. If damages fall more severely on the future poor, they may end up sufficiently badly off that their fate justifies a greater concern when inequality aversion is greater.

However, at a zero rate of time preference (the left column) the Ramsey Equation seems to dominate, even at the inversely proportional damage. In addition, in the bottom row where damages are proportional to income (which corresponds to RICE optima given that $\xi = \omega = 1$, as explained in the previous section), an increase in η is also followed by a reduction in tax as expected from the Ramsey Equation. This is because, even if inequalities are accounted for, the growth rate is the same for rich and poor (this also involves the assumption of proportional distribution of abatement costs), so that the Ramsey Equation applies. There are different damage functions for the various regions (reproduced from RICE), but they are not sufficiently different to generate a special concern for the impacts of climate change on the poor regions. This shows that the Schelling Reversal does not occur in RICE with the damage functions of that model, and thus that the representation of inequalities in NICE are needed in order to observe the reversal. (One could perhaps obtain the reversal with $\xi = \omega = 1$ if one adopted much more severe damage functions for the poor regions of the world than in RICE. We do not consider such modifications in this paper.)

Understanding this is instructive. One might initially think that if inequality matters more at high η and the strong distributional effects come in the future, then the effect of a skewed distribution on marginal damages should be highest at a zero time preference rate.

The missing component in that intuitive argument is that mitigation effort is a balance between marginal mitigation cost and marginal damage. At a zero rate of time preference the optimal mitigation effort is high as is the growth rate (due to lower damages). This means future consumption is higher and damages are lower across quintiles, setting the stage for increases in inequality aversion to be dominated by the intergenerational inequality. When the rate of time preference is higher, mitigation and growth rates are lower, allowing the intragenerational distribution to dominate when there is an increase in inequality aversion. Moreover, when future consumption levels are lower, damages increase inequality more when they are equal across quintiles (ξ = 0) or inversely proportional to income (ξ = -1), reinforcing the importance of future inequalities.

This explains why the Schelling Reversal (greater inequality aversion raises mitigation efforts) appears here only when time preference is high enough (and, of course, when damages hurt the poor disproportionately).

As we can see from Figure 1, the higher η, the more important it is to get the correct value of ξ. In the case $\rho = 0$, $\eta = 2$, the difference in the 2015 carbon tax between $\xi = 1$ and $\xi = -1$ is 635 $/tC, in increase of almost 700%. In terms of abatement, the difference is between fully mitigating in 30 years or a century later than that.[9]

3.2 Interactions with the Distribution of Mitigation Cost

We now evaluate the Schelling Reversal under different assumptions about the distribution of mitigation cost between income strata. Figure 2 reproduces Figure 1 under another salient value of ω, namely, 2.[10] With $\omega = 2$, the relative cost of mitigation with respect to income is itself proportional to income: if a person loses 3% of her income to mitigation efforts, a person that is twice as rich will lose 6%.

We see clearly that the value of ω tends to have the opposite effect on the optimal tax rate than the value of ξ. Less damage to the poor from adverse climate effects will justify more lenient mitigation policy, but if the distribution of abatement costs spares the poor, the rate of mitigation will be increased. However, both parameters respond to increasing η: larger η leads to an increased salience of both ξ and ω.

Unsurprisingly, for a given level of (non-trivial) inequality aversion η, and specified discount rates (ρ), the highest carbon tax rate emerges for high ω (abatement costs are disproportionately levied on the wealthy) and low ξ (climate damages disproportionately affect the poor). Conversely, the lowest tax rates emerge from a scenario with low ω and high ξ.

In order for the Schelling reversal (increasing η leads to higher tax rates) to emerge in this framework, ξ must be small enough and ω must be large enough. Further, we observe that the larger the value of the difference $\xi - \omega$, the lower the rate of time preference at which the Schelling reversal can emerge, emerging even at zero time preference when $\xi < 1$ and $\omega = 2$. We conjecture that the Schelling Reversal would occur more easily with a carbon tax combined with other sufficiently progressive compensatory measures, such as a redistribution of the revenues from the tax that makes all but the richest quintile net beneficiaries (Metcalf 2009, Sterner 2012, Wilkerson et. al. 2015, Williams et al. 2014).

[9] If there were no inequality aversion ($\eta = 0$), the value of the income elasticity of damage ξ would not be of any importance, and the mitigation effort would be very high, as we show in Figure A1 of the online appendix.
[10] In the online appendix, the figure for the case $\omega = 0$ is also provided.

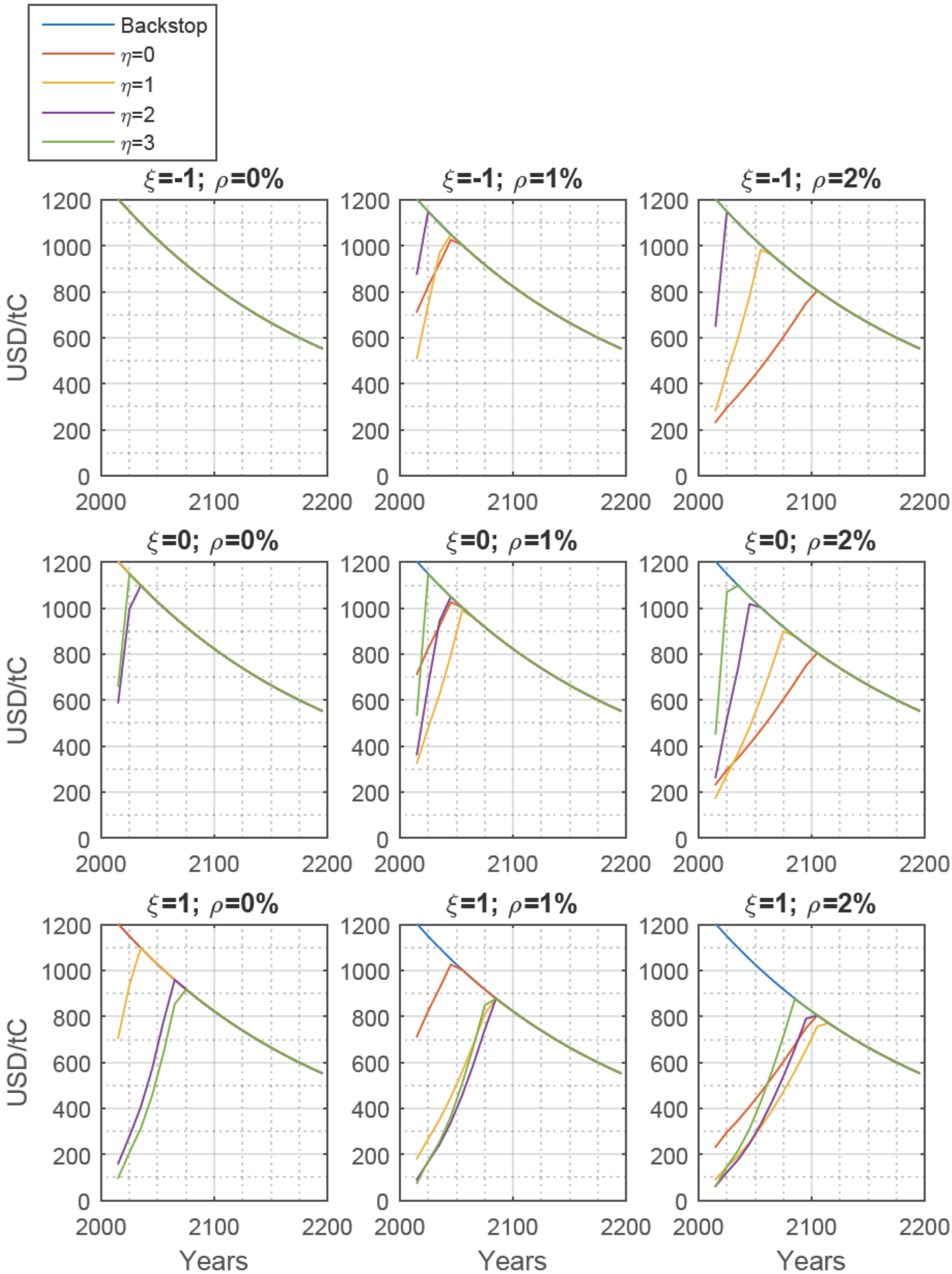

Figure 2: Optimal carbon taxes as a function of ρ, η, and ξ (for ω = 2).

Altogether, the results of this section and the previous one reveal the supreme importance of the distribution in income, damages, and mitigation costs in the determination of the optimal carbon tax. These considerations have been neglected in the research on carbon pricing. The empirical and ethical issues surrounding inequalities deserve more attention.

3.3: Interactions with Catastrophic Damages

As mentioned before, we add a higher order damage term — à la Weitzman 2012 — and compare optimal policies across specifications. Much like with pure time preference, the direction of the effect is obvious. As we change from the standard damage function to the modified version with 50% damage at 6°C (increase above pre-industrial levels), and from there to 50% damage at 4°C, the optimal mitigation rates increase. However, surprisingly, for most reasonable values taken by the other parameters, the effect of adding such huge damages *with certainty* has a comparatively small effect in the optima when compared with the effect of the other parameters investigated here.

In Figure 3 we plot the optimal taxes for different assumptions about the total damage (while assuming ω = 1 and a 1% rate of time preference). The damages distinguish themselves by the coefficient on a seventh power of the temperature, $\alpha_{U,}$ which introduces a huge convexity in damage at a point. As noted, the coefficients are calculated to get 50% damage to global output at a 6°C (as in Weitzman 2012), or at 4°C (Dietz and Stern 2014). (These assumptions are described in more detail in the online appendix.)

For the top two rows, where ξ = -1 and 0, respectively, the differences in optimal tax between these damage functions are quite minimal, as are the differences in optimal tax between the different values of ξ. In these scenarios, the additional damage never leads to more than a reduction in time needed to reach full mitigation by more than a decade, despite the very large differences in the damage function.

By contrast, for the bottom row, where damages are proportional, the differences between damage functions and different values of η have larger implications for the optimal tax.

As will appear clearly below, the reason for this result is that when damages fall disproportionately on the poor, the mitigation policy is strong enough and temperatures moderate enough along the optimal path to avoid any significant influence of the extra convex term in the damage function. The skewed distribution of impacts on the poor produces a sufficient potential social catastrophe, so that avoiding it also prevents the catastrophic term in the total damage function from being relevant.

If, however, damages are proportional (the bottom row), the optimal tax rate and mitigation effort will be smaller, and thus temperatures will rise to a point at which the Weitzman and Dietz-Stern damage functions depart from those of RICE2010. In this scenario, the degree of inequality aversion and the actual damage response to temperature matter more.

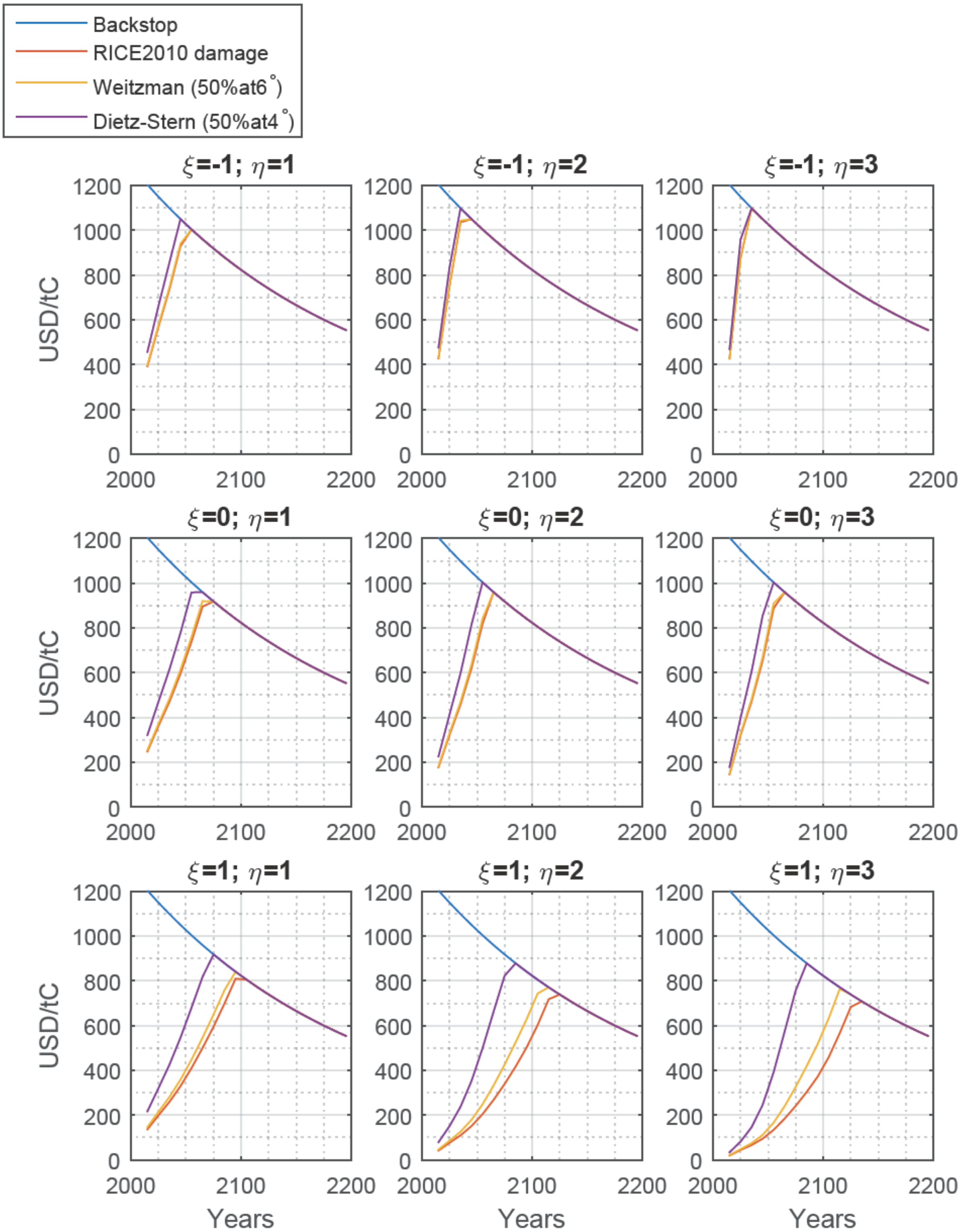

Figure 3: Carbon taxes as a function of ξ and η under standard and catastrophic damages (the value of ρ is 1%, ω is 1)

Weitzman 2007 disagreed strongly with the authors of the Stern Review regarding their choice of normative parameters (ρ and η), but agreed to some extent that high levels of effort are warranted if uncertainty is taken into account, with the low probability of very strong damages on aggregate output. This can be seen in the bottom rightmost plot of

Figure 3. The normative parameters and damage *distribution* assumptions are similar to what Weitzman had in mind, and there is a clear effect.

However, a comparison between Figures 1 and 3 shows that while the possibility of larger damages are important to the optimal mitigation effort, the possibility of damages disproportionately affecting the poor has a much larger impact on the optimum, regardless of the values taken by the normative parameters.[11] This is an important lesson. By neglecting the intra-generational distribution of inequalities (within regions and countries), the literature had to look at global catastrophes in order to explore potential reasons for strong mitigation. With inequalities and a skewed damage distribution, the social catastrophe looms even at less extreme temperature increases.

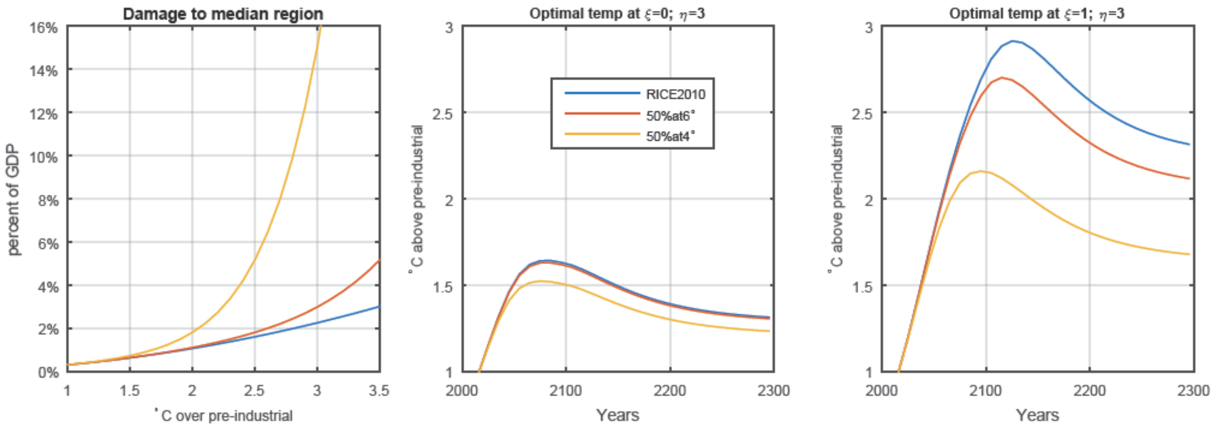

Figure 4: Damage functions and the corresponding optimal temperatures. The first panel shows the three damage functions for the median region. The second panel shows the temperatures for the paths in the bottom middle panel in Figure 3. The third panel shows the temperature paths for the bottom rightmost panel in Figure 3.

The results in Figure 3 are best explained by looking at the temperatures and damage functions. As can be seen from leftmost panel of Figure 4, there is hardly a difference between the three damage functions below 1.5°C. Any mitigation path that avoids higher temperatures even for the RICE2010 damages will not change perceptively when the higher order damage term is introduced. That is the case for the leftmost column of Figure 3. The difference between Weitzman (50% at 6°C) and RICE2010 only becomes noticeable past 2.5°C. As shown in the rightmost panel of Figure 4, the RICE2010 temperature path for the bottom right panel in Figure 3 exceeds this, which explains why the paths for the three damages are significantly different.

We note that while this analysis holds for optimal carbon taxes, the economic damage that results from having a non-optimal policy (that is too lax) may be quite large and significantly affected by the alternative assumptions about damage considered here. Incorporating uncertainty over the damage function and other key parameters (including climate

[11] With the exception of $\eta = 0$, in which case the distribution of damage is irrelevant, and the mitigation effort very high, as shown in the online appendix.

sensitivity and other parameters not even discussed here) might also lead to a stronger policy response.

4. Conclusions

We have investigated the interactions between a number of factors that can, in isolation, have an important effect on the strength of optimal mitigation – namely, pure time preference, inequality aversion, inequalities in the distribution of both damage and mitigation cost between rich and poor, and a damage function that does or does not assume catastrophic impacts at high global mean temperatures increases. We have shown the comparative importance of these factors by displaying optimal carbon price trajectories that arise from the wide variety of combinations that are possible given the primary range of disagreement over each factor.

To frame the discussion, we began by articulating Schelling's conjecture that properly accounting for inequalities could lead the inequality aversion parameter to have an effect opposite to what is suggested by the Ramsey Equation. We explained how NICE allows for a particularly rich investigation of the conditions under which this reversal may occur, by examining the interaction of pure time preference ρ, inequality aversion η, and the distribution of climate damages and mitigation cost ξ and ω. We showed that the Schelling Reversal does indeed happen but only when a set of conditions are all satisfied: roughly, when pure time preference is non-zero, climate damages disproportionately harm the poor, and mitigation costs are not disproportionately paid by the poor; in these circumstances, increasing inequality aversion leads to faster mitigation. Otherwise, intergenerational inequalities tend to dominate. The Schelling Reversal emerges especially strongly in situations of a progressive distribution of abatement costs and a regressive distribution of climate damages.

We also showed that for most values taken by the other parameters, the effect on optimal policy of adding catastrophic damages with certainty at 4° or 6°C above preindustrial temperatures typically has a smaller effect than the other parameters investigated here, especially when compared to the effect of sub-regional inequalities. The addition of potentially catastrophic damages has a larger effect on optimal policy when damages are proportional to income than when they fall more on the poor, because the latter requires strong mitigation for reasons independent of the potential for catastrophic damages, which prevents temperature from increasing to the point where the elevated damage function would be relevant. However, we note that our experiments are deterministic and do not explore the economic consequences of non-optimal carbon policies, both of which are important further issues, which we explore in work in progress.

In sum, NICE provides answers to a number of pressing questions about the comparative importance of familiar factors such as discounting and higher order damage terms. It also emphasizes the potential greater importance of a factor largely ignored in existing IAMs: the interaction between climate change and inequalities within regions and countries.

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Online Appendix

1. The NICE Model

In this section we describe the NICE model that is used in our analysis, which evaluates public policy with a social welfare function. Following RICE2010 (Nordhaus 2010), on which NICE is based, and most of the literature, we use a discounted and separable constant elasticity function with population weights:

$$W\left(c_{ijt}\right) = \sum_{ijt} \frac{L_{ijt}}{(1+\rho)^t} \frac{c_{ijt}^{1-\eta}}{1-\eta} \tag{1}$$

where W denotes social welfare, L population, c per capita consumption, ρ the rate of pure time preference and η inequality aversion. The subscripts i, j, and t are the region, quintile, and time indices respectively.

In RICE the social objective is not clearly distinguished from the preferences of infinitely-lived representative agents. In NICE we decouple the behaviour of the private sector from the social welfare evaluation, so that when we change a parameter in the social welfare function (discount rate or inequality aversion), this triggers no change in the private preferences of the individual agents about intertemporal allocation and savings. Savings in NICE are not determined by the social welfare function but by a different (positive) utility function which is a discounted sum of the logarithm of consumption, with a utility discount rate equal to 1.5%.

In NICE, the world is composed of the same twelve macro region economies as in RICE2010 (some of which are in fact countries, like China, India, the USA, Russia, and Japan). In order to investigate the ways in which climate interacts with a more fine-grained representation of inequality, we further refine this with a sub-regional description of consumption distribution. We construct current quintile distributions for all RICE2010 regions based on World Bank Development Indicators data on income distribution by country (World Bank 2014). We assume that these distributions are a proxy for consumption distributions before accounting for climate damages and mitigation cost, and remain constant into the future.[12] On that basis we compute pre-damage and pre-mitigation cost per capita consumption level per quintile from each region's per capita consumption in each period. (Note here and in the equations that follow that this leaves regional climate and economy aggregates as computed in RICE2010.)

The equations in NICE that are most relevant to the current analysis are the social welfare function (equation 1 above), the equations for regional aggregates that mirror RICE2010

[12] The assumption that they remain constant is motivated by the fact that, whereas one can hope for the inequalities across regions to decrease in the future (as assumed in RICE and reproduced in NICE) as a result of economic and technological convergence, the inequalities within countries are submitted to opposing forces which make it equally likely to observe changes in either direction.

(equations 2-4 below), the novel equations in NICE that allow representation of sub-regional inequalities (equations 5-7 below), and a revised damage function (equation 8 below) that allows investigation of alternative assumptions about catastrophic damage to be compared to those of RICE2010.

Given pre-damage and pre-mitigation cost gross output Q_{it} in region i at time t, the post-damage and post-mitigation cost net output is

$$Y_{it} = \left(\frac{1-\Lambda_{it}}{1+D_{it}}\right) Q_{it} \quad (2)$$

where D_{it} is regional damage and Λ_{it} is regional mitigation cost. For regional population L_{it} and savings rate s_{it}, investment is

$$I_{it} = s_{it} Y_{it} \quad (3)$$

and average per capita consumption (for region i at time t) is

$$\bar{c}_{it} = \frac{1-s_{it}}{L_{it}} Y_{it} \quad (4)$$

From here, the first novel equation of NICE computes disaggregated per capita consumption per quintile j pre-damage and pre-mitigation cost by

$$c_{ijt}^{pre} = 5\bar{c}_{it} \left(\frac{1+D_{it}}{1-\Lambda_{it}}\right) q_{ij} \quad (5)$$

where q_{ij} is the income share of the jth quintile in region i.[13]

Post-damage and post-mitigation cost average per capita consumption (for quintile j in region i at time t) is

$$c_{ijt} = \frac{5\bar{c}_{it}}{1-\Lambda_{it}} \left((1+D_{it})q_{ij} - (1-\Lambda_{it})D_{it}d_{ij} - (1+D_{it})\Lambda_{it}e_{ij}\right) \quad (6)$$

where d_{ij} is the share of damages and e_{ij} is the share of mitigation cost of the jth quintile in region i. These quintile shares of damage and mitigation cost are computed for different values of new elasticity parameters ξ and ω introduced here such that

$$d_{ij} = k_{i\xi} q_{ij}^{\xi}; \quad e_{ij} = k_{i\omega} q_{ij}^{\omega}. \quad (7)$$[14]

This yields a constant elasticity relationship for the quintile damage and mitigation cost shares as a function of income. By modifying the parameters ξ and ω, we are thus able to vary the distribution between quintiles of climate damages and mitigation costs. For $\xi = 1$, regional damages are distributed proportional to consumption; for $\xi = -1$, inversely

[13] The quintile share q_{ij} is multiplied by 5 in order to obtain per capita values (e.g., if $q_{ij} = 1/5$, the per capita consumption in the quintile is equal to the per capita consumption in the whole population).

[14] For equation 7, the parameter values $k_{i\xi}$ and $k_{i\omega}$ are chosen such that $\sum_j d_{ij} = 1$ and $\sum_j e_{ij} = 1$ respectively.

proportional. For $\omega = 0$, abatement costs fall in equal amounts on rich and poor quintiles; for $\omega = 2$, they fall much more on the rich.

Recent literature has suggested that the economic consequences of climate change may be more pronounced than previously thought, and become larger and more uncertain at greater departures from preindustrial temperatures (Houser et. al. 2014, Burke et. al. 2015). This has motivated some economists to argue for the importance of using a "fat-tail" approach to modelling the risk of low probability but very high impact scenarios that may emerge from an altered climate (Weitzman 2011, 2013).

In RICE2010, the function determining the damage term D_{it} is a quadratic function of temperature rise above preindustrial levels (T):

$$D_{it} = \alpha_{1i}T_t + \alpha_{2i}T_t^2$$

Its coefficients are based on the empirical estimates described in the introduction, which have a domain of approximate validity near and below 2.5°C (above T) (Tol 2009, Nordhaus 2013). In an effort to model the possibility of extreme damage beyond that domain, but lacking much empirical basis for extrapolation, (Weitzman (2012)) proposed adding a higher order temperature term based on a thought experiment of what could happen at a temperature of 6°C. To this end, in NICE, we add an additional term to the RICE2010 damage function that applies a coefficient to temperature raised to the 7th power, in order to explicitly consider the possibility that climate change could have a much more catastrophic impact on the global economy:

$$D_{it} = \alpha_{1i}T_t + \alpha_{2i}T_t^2 + \alpha_U T_t^7 \quad (8)$$[15]

Weitzman 2012 supposes that damages equal to 50% of gross output would occur at T = 6°C. In a recent paper focusing on damages on capital, Dietz and Stern (2014) imagine an even gloomier calibration with 50% damage at T = 4°C. We consider optimal taxes for all three of these specifications: original RICE2010, Weitzman, and Dietz-Stern, and calibrate the α_U parameter accordingly. (For the Weitzman case α_U= 3.3615e-06. For the Dietz-Stern case α_U= 5.8707e-05.)

An additional departure from RICE2010 introduced into NICE in these model runs is that here we assume a single backstop price for all regions equal to the backstop price William Nordhaus assumes in DICE2010, which is aggregated from the differing regional backstop prices in RICE2010.

The preceding paragraphs summarize the key features of NICE relevant to the analysis in this paper. Additional technical discussion of NICE and its relation to RICE2010 is available in the methods, appendix, and online supplement of Dennig et. al. 2015.

[15] In the RICE model, the damage coefficients on the linear and quadratic terms are region specific. In our initial exploration here, this added α_U term is not regionally specific but rather indicates damage to the global economy as a result of climate change.

2: Varying Pure Time Preference Only, With No Inequality Aversion

The Schelling Reversal points to the importance of η, the inequality aversion parameter. But the pure rate of time preference ρ adds a temporal form of inequality aversion in the presence of growth, and this somewhat complicates the analysis. There is an ethical argument for keeping ρ low, since the only uncontroversial reason to give less weight to future generations is that their existence is uncertain for the coming centuries. But there are also arguments for a higher value of ρ (Arrow 1999, Nordhaus 2007), and so we investigate values of ρ between 0 and 2, as this represents the range of values at stake between leading commentators (Stern 2006, Nordhaus 2010).[16] There is also some argument in the literature that the discount rate should decline over time because of the uncertainty regarding future rate of economic growth (Arrow et. al. 2012). Exploring multiple parameter values of ρ may help to inform this discussion.

In this section, we explore the sensitivity of optimal policy with respect only to the rate of pure time preference ρ by setting inequality aversion η = 0 and holding all other parameter values fixed, including assuming here that there is no climate catastrophe (α_U = 0). These assumptions imply that the distribution of climate damages, ξ, and abatement costs, ω, do not matter, as such a social objective is concerned only with maximising total (possibly discounted by time preference) output. Figure A1 shows the optimal taxes for different discount rates.

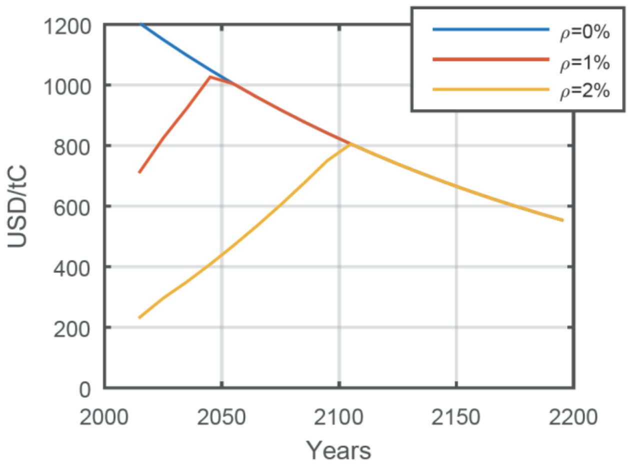

Figure A1: Mitigation with no inequality aversion (η = 0) and rates of pure time preference ρ = 0, 1%, and 2%.

[16] Note that even Stern's very low value of 0.1% for ρ nonetheless implies that extinction has almost 10% chance of occurring in a century if one assumes, as Stern does, that the probability of extinction is the only sound basis for time discounting. Alternative normative frameworks to Stern's zero time preference utilitarianism that involve higher values for ρ include agent-relative welfarism (Arrow 1999) and non-welfarist arguments, e.g., libertarian ideas about the right of each individual to keep his property. Alternatively, one might argue that regardless of ethical arguments, political justification ultimately requires deference to the actual shared values of society, which arguably reveal a positive rate of pure time preference (compare Nordhaus 2007, Weitzman 2007, Rawls 1971).

The line descending from 1,700 to 800 USD is the carbon price at which full mitigation is achieved globally. It is known as the backstop price, and is exogenously given in RICE and NICE. Notice that with no time discounting via ρ, if one does not care about inequality by setting $\eta = 0$, immediate *full* mitigation would be warranted by the economic costs and benefits embodied in these integrated assessment models.[17] At $\rho = 1\%$, the carbon taxes are still an order of magnitude greater than is currently under debate, with full mitigation well before the end of the century. At the large $\rho = 2\%$, under which society is valuing utility in a century at a little more than a tenth the current value, one still gets mitigation at the upper end of what is currently being debated.

This illustrates that if society were to care only about costs and benefits in the Kaldor-Hicks sense (Kaldor, 1939; Hicks, 1939), where the gains to the winners must simply be sufficient to hypothetically compensate the losers, then serious mitigation action would be the theoretically optimal policy response. However, the Kaldor-Hicks approach ignores that when the losers are not compensated, their losses may loom large in comparison to the others' gains. According to the social objective (1), one ought to care about where in the income distribution the costs and benefits accrue.

It has been argued that due to growth, moving from the Kaldor-Hicks approach to the social objective (1) would lead to significantly lower mitigation levels. Because the costs of mitigation fall on the current generation, and the benefits on future, in all likelihood richer generations, the resulting adjustment is in favor of less mitigation, or so the argument goes (Dasgupta 2007, 2008, Nordhaus 2007).

As shown in the paper, this is based on an incomplete picture of the inequalities involved in climate change. Indeed, following Schelling (1995) it is arguably inconsistent to invoke the relative affluence of future generations in the debate about mitigation without going all the way to a full analysis of distributional issues, including *within* generations. Performing such an analysis also highlights that it is questionable to use the pure time preference parameter ρ, which is blind to the well-being of future generations, to take care of this issue of relative affluence. The inequality aversion parameter η is more appropriate for this task.

3. Results for the case $\omega = 0$

This case corresponds to a situation in which the rise in energy prices and other economic impacts (wage stagnation, unemployment) affect the poor disproportionately, so that everyone in the society bears the same absolute abatement cost.

[17] These models do not adequately incorporate the cost of adjustment to such a drastically different energy regime, especially in early time periods. The mitigation cost being counted is the cost of deploying the best substitute available at that carbon price, as if the technology could be scaled up instantly. This also arguably does not price in the risk of a mismanaged switch to renewables, which is significant if the change is very fast.

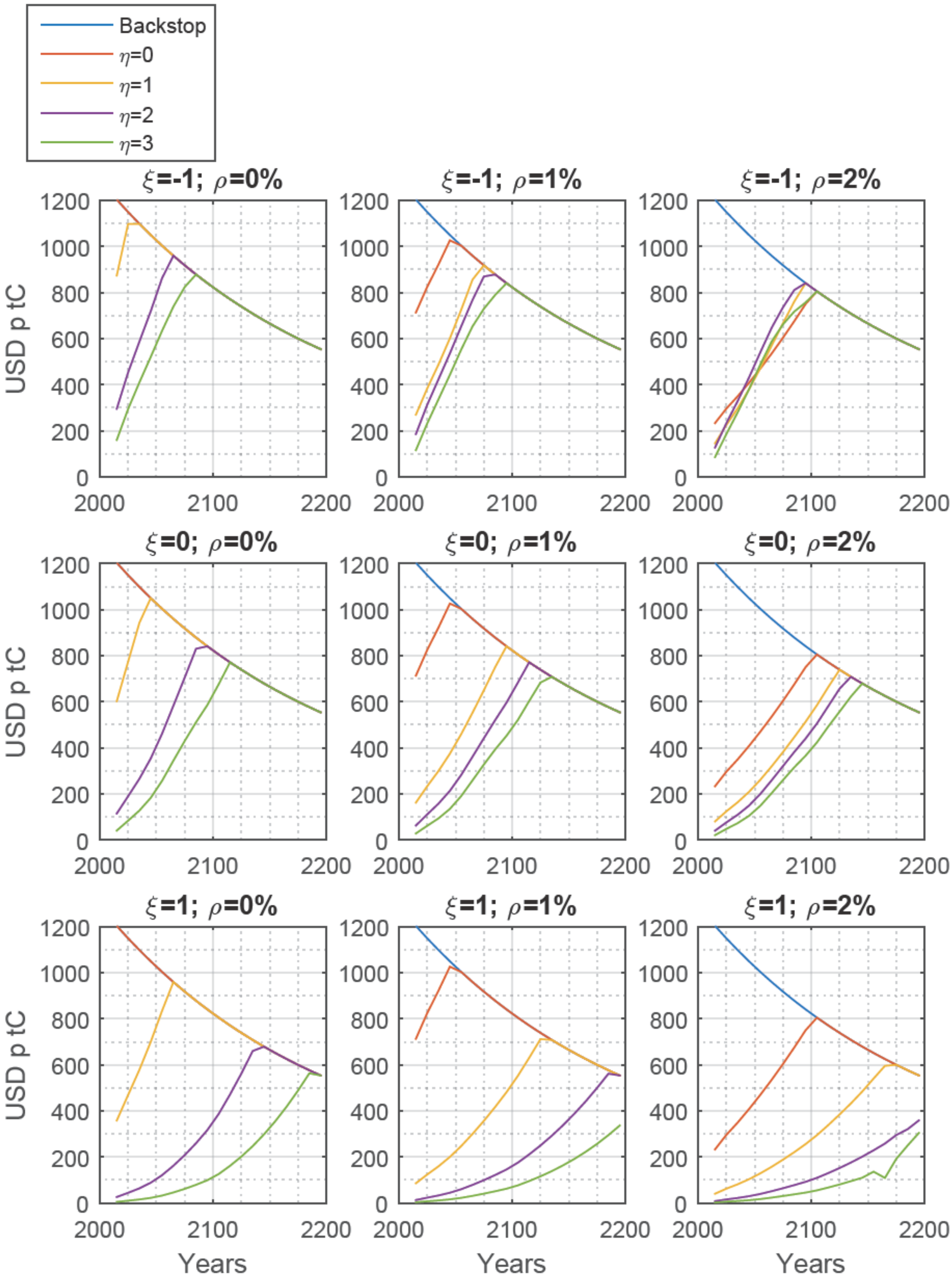

Figure A2: Optimal carbon taxes as a function of ρ, η, and ξ (for $\omega = 0$).