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Abstract

Policy makers concerned with setting optimal values for carbon instruments to address climate change externalities often employ integrated assessment models (IAMs). While these models differ on their assumptions of climate damage impacts, discounting and technology, they conform on their assumption of complete markets and a representative household. In the face of global inequality and significant vulnerability of asset poor households, we relax the complete markets assumption and introduce a realistic degree of global household inequality. A simple experiment of introducing a range of global carbon taxes shows a household's position on the global wealth distribution predicts the identity of their most-preferred carbon price. Specifically, poor agents prefer strong public action against climate change to mitigate the risk for which they are implicitly more vulnerable. This preference exists even without progressive redistribution of the revenue. We find the carbon tax partially fills the role of insurance, reducing the volatility of future welfare. It is this role that drives the wedge between rich and poor households' policy preferences, where rich households' preferences closely mimic the representative agent. Estimates of the optimal carbon tax and the welfare gains of mitigation strategies may be underestimated if this channel is not taken into account.

Keywords: Climate change, Inequality, Risk, Optimal carbon policy
JEL Classification: H23, H31, Q54, Q58

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1 Introduction

To date, models of climate and the economy have calculated optimal carbon policy under the assumption of complete markets and a representative agent. A growing empirical literature on climate impacts highlights the distributional costs of climate change, with the global poor being particularly vulnerable. In order to explore the implications of relaxing these assumptions from the integrated assessment modelling literature, we introduce a standard incomplete markets framework. Thus, in addition to an uncertain global climate state, households also face idiosyncratic productivity shocks for which they can not insure away. Calibrating the model to the global economy, we find that there are significant differences in the cost of carbon faced across the wealth distribution driven implicitly by individual vulnerability. Poor households are vulnerable to future shocks, due to their relative paucity in private insurance. Hence, poor households prefer *ex ante* stronger public action through high carbon taxation, even in the absence of progressive redistribution. However, the direction and predictability of future transfers are of primary concern in the identity of a household's most preferred carbon policy. In this setting, the public insurance co-benefit yields large welfare gains for vulnerable households.

The International Panel on Climate Change (IPCC) details the impact (both realized and potential) on the world's more vulnerable population, in its chapter on Livelihoods and Poverty in the 2014 Climate Change Report[1]. In this chapter the report discusses the interaction of climate change and the challenges faced by the poor and economically vulnerable. While climate change implies specific threats related to shifting weather patterns, increased incidence of natural disasters, decreased land arability, etc., the report also notes that climate change exacerbates existing vulnerabilities experienced by the poor. While there will be regional heterogeneity in climate change, the impact will be felt globally: the poor in all regions will suffer from market disruption, declining agricultural yields, reduced access to water, etc. Indeed, while poor households in low income countries (LICs) will incur the greatest costs of climate change impacts, the IPCC notes that inhabitants of some middle income countries (MICs), including urban Chinese, are among the most at risk to climate-related impacts.

One popular tool for policy makers is the integrated assessment model (IAM)[2], which aims to capture the features of the climate change problem, including: modelling the carbon system; atmospheric carbon's relationship to global temperature; temperature's relationship to welfare

[1]See Olsson et al. (2014)

[2]e.g. Dynamic Integrated Climate-Economy model DICE, Nordhaus and Sztorc (2013); Climate Framework for Uncertainty, Negotiation and Distribution, FUND, Tol (1997), and Golosov et al. (2014)

loss; and the economic system, including modelling the micro-foundations of savings and fossil fuel use. There are a wide range of IAMs, which differ on the assumptions they make; however, a common feature of these models is their reliance on a representative agent assumption for assessing consumer behaviour and welfare impacts. While there has been a trend towards providing regional detail, the unit of analysis remains nation states or regional blocs[3] . In this paper, we change the unit of analysis to individual households that experience varying degrees of vulnerability in the face of their economic decisions and the threat of climate change.

Climate change impacts are likely to vary significantly across the population, depending on household characteristics, including: location, occupation, wealth, etc. This paper focuses primarily on wealth inequality. It looks to address the question of how a realistic distribution of household wealth changes the optimal carbon taxation problem, from the familiar representative agent framework. It seeks to answer both *how* and *how much* inequality matters for optimal carbon taxation. The primary channel we investigate is the cost that risk imposes across the population, and the role carbon taxation can play as public insurance. When capital markets are incomplete, households need to take precautionary action to insure against idiosyncratic shocks. Moving assets to the future then becomes a question of consumption smoothing, aggregate risk mitigation[4], and insurance against idiosyncratic shocks. It is this last component that is absent from the current body of literature on optimal carbon taxation.

Models with incomplete markets and heterogeneous households have become common in more traditional research areas of macroeconomics, allowing a better understanding of distributional impacts and implications of public policy. These types of models offer insights into the role of public policy as a way of mitigating risks through, for example, social security and progressive taxation (see Heathcote et al. (2009) for an introduction). Climate policy can play a similar role. In light of poor households' explicit vulnerability to climate change, relaxing the representative agent assumption seems a natural progression for IAMs, used for assessing the welfare impacts of climate change, and delivering estimates for the optimal policy response. In general, aggregation will miss the nuances of household behaviour and welfare implications across the distribution. Currently there is little in the literature that explicitly models how climate change variously affects different people, especially through climate risk and individual uncertainty.

In order to explore these implications, we present a simple integrated assessment model that

[3]e.g. RICE Nordhaus and Yang (1996), WITCH Bosetti et al. (2006), and REMIND Leimbach et al. (2010)

[4]See Gerst et al. (2010) and Howarth et al. (2014) for examples of how aggregate risk impacts the social cost of carbon and policy decisions with regards to climate change mitigation.

encompasses the carbon, climate and economic systems. The model is calibrated to match: a global CO_2 emissions path scenario from the IPCC, aggregate risk and damage estimates from the IAM literature, and moments from the global distribution of income and wealth. The model includes both aggregate climate risk and idiosyncratic household productivity shocks, which may be correlated. The primary exercise is to evaluate a range of global carbon taxes, observe household welfare responses, and identify their most preferred policy.

This policy preference depends on both the characteristics of the household and the policy. The carbon tax is determined in advance of the period in which it applies; thus, household welfare is considered *ex ante*. In order to isolate the impact of wealth inequality on the identity of a household's most-preferred tax, we initially suppress the revenue redistribution channel and equalize idiosyncratic risk-profiles. In this analysis, households differ only on their wealth endowment; a determinant of their ability to self-insure. Clearly, *ex post* redistribution of the tax revenue can be a significant contributor to the distribution of welfare impacts. However, thorough analysis of revenue recycling, double-dividends, and interaction with other distortionary taxation is beyond the scope of this study.

Our first finding is that when idiosyncratic risk is correlated with aggregate risk, such that the variance of a household's future labour income increases in a bad aggregate state, the dispersion of the population's tax preference becomes large and quantitatively relevant. This result arises from the way an increase in the risk on labour earnings affects households along the distribution of wealth. Increasing the carbon tax decreases earnings volatility and allows households to reduce their costly precautionary savings. This effect is larger for households who receive a relatively large proportion of their earnings from labour - i.e. the poor.

Our second finding is that the economic vulnerability of poor households in the standard incomplete markets framework creates a role for carbon taxation as a form of public insurance that can substitute for private savings. Carbon taxation reduces the impact of extreme climate realizations on earnings. However, quantitatively, the direction of transfers inherent in the carbon tax rebate is the most important factor in a household's policy preference arising from climate-related damages. In addition, the predictability of these future transfers is also of key concern. For today's wealthiest households, if the future carbon tax rebate is sufficiently uncertain, they would rather no public intervention in climate change at all.

In comparison to the more familiar setting of complete insurance markets and a representative agent, the optimal carbon tax under such assumptions resembles the preference of only the most wealthy households in the experiments allowing for household inequality. This implies that introducing risk and inequality can substantially change the calculus of optimal carbon taxation, and also that the direction and predictability of carbon revenue redistribution should be of first order consideration to policy makers.

2 Background

A growing empirical literature on the impacts of climate change identifies significant distributional considerations. As mentioned above, the IPCC notes that the global poor will be especially susceptible to decreasing agricultural yields, access to clean drinking water, and global market disruption. Skoufias (2012) summarizes some of the quantitative evidence on the welfare impacts of climate change, particularly with respect to global poverty. The author notes that there are sectoral considerations, particularly with respect to decreasing agricultural productivity. However, the most vulnerable population may be urban wage-labourers, who are particularly exposed to food price shocks. The global demographic shift towards urbanization also implies that this could be a key driver on climate change's influence on poverty metrics. Dell et al. (2013) review the empirical literature on weather shocks and climate impacts. Several of the channels through which weather can impact welfare include: labour productivity, health and mortality, and industrial and services output. While not addressing household inequality directly, the authors do note that climate impacts are likely heterogeneous, with damage being higher for low income countries. On longer horizons, climate-induced health shocks can create linked generational issues. Weather shocks, which create better conditions for disease vectors or decrease maternal and infant nutrition, can have effects on infant mortality as well as long-run implications for adult outcomes (e.g. education, wealth, health and mortality).

2.1 Related literature

Recent work related to this topic has looked at environmental taxes in the context of distributional issues for public finance. Fremstad and Paul (2019) examine carbon taxation in an input-output model of the US and look at the impacts of on a range of socio-economic characteristics while, Bosetti and Maffezzoli (2013) and Fried et al. (2018) use an incomplete markets framework and examine the distributional impacts of various carbon taxation schemes. None of these studies present an IAM, or indeed an externality, the aim not being to derive an optimal tax, but rather to explore the implications of a potentially regressive environmental tax policy and the potential for double dividends through various revenue recycling schemes. In contrast we hold constant the fiscal structure of the global economy, and only allow climate specific taxation to vary.

This paper is also closely related to the work done on expanding IAMs to account for heterogeneity of impacts. Models with regional heterogeneity, such as RICE and FUND, account for geographical heterogeneity, and can be used to make assessments of the distributional impacts of climate change on poverty-related metrics, as in Skoufias (2012). Anthoff et al. (2009a) use an IAM framework with diminishing marginal utility and equity weighting to discuss and quantify the implications of global income inequality across many regions. To our knowledge, however, no study has relaxed the representative agent assumption in an IAM framework, and thus welfare analysis relies on aggregates, such as the elasticity of a poverty count to changes in GDP.

A recent study, Dennig et al. (2015) acknowledging the need to move beyond regional aggregation, explores an alternative to the standard RICE framework by incorporating income inequality *within* regions. In the likely case that damages are greater for the poor within a region, the authors find that the optimal carbon tax would be well in excess of the case which does not account for intra-regional income inequality. While similar in spirit our work differs from this in several key ways: we focus on individual household behaviour in the face of incomplete insurance markets, rather than representative agents of regional income quintiles. We do not currently explore regional climate damage heterogeneity, or formulate an explicitly regressive climate damage. And in our framework, the savings decision for each household is endogenous to the climate policy rather than a fixed proportion of income, which ends up being a key channel through which inequality drives policy impacts. Finally, our analysis focuses on *ex ante* impacts caused by un-insurable risk. Therefore, our contribution is from the perspective of today's poor, rather than ex post analysis of the impact on the future poor.

3 The Framework

In order to address the question on how optimal carbon policy setting responds to changes in household wealth inequality, we propose the following simple dynamic framework, which adopts much of the structure from Golosov et al. (2014). The model is a dynamic stochastic general equilibrium model, which includes a simple description of climate change mechanics and allows for heterogeneous households. Thus it features a dynamic decision on household consumption and savings, including a precautionary motive for individual risk. Competitive firms use fossil energy as an input in production that increases the stock of greenhouse gases (GHGs) in the atmosphere, which accumulate over time and increase global mean temperature. The increase in temperature has a negative impact on aggregate production. Finally, there exists an aggregate shock related to the climate change externality, such that today's decision makers don't know the severity of the future temperature increase.

While the framework is dynamic, the time horizon is finite and for the purposes of this exercise we limit the number of periods to two. Working with household inequality and aggregate risk is challenging, and especially so in a climate change framework, where households without perfect foresight need to form expectations about the evolution of the atmospheric carbon stock as well as the aggregate stock of capital. This limited time horizon is sufficient for exploring the implications of income and climate risk across the distribution of households, and we conjecture that the findings of the two period model will carry over to longer horizons.

3.1 Households

Each household i chooses a sequence of consumption, $c_{i,t}$ and savings, $k_{i,t+1}$ to maximise their expected lifetime utility taking aggregate prices, w_t and, r_t, as given. It solves:

$$\max_{c_{i,t}, k_{i,t+1}} \quad \sum_{t=1}^{T} \beta^{t-1} \mathbf{E}[u(c_{i,t})] \tag{1}$$

$$\text{s.t.} \quad c_{i,t} + k_{i,t+1} = (1 + r_t - \delta)k_{i,t} + w_t l_{i,t} h_{i,t} + g_{i,t}$$

$$k_{i,t+1} \geq -b$$

where the households supply their period t labour endowment, $l_{i,t}$, (normalized to 1) inelastically. As in Bewley-Aiyagari-Hugget-type models, $h_{i,t}$ is an idiosyncratic labour productivity state that modifies an agent's labour income through the *effective* supply. Agents also have different wealth holdings, where k_0 is an initial endowment. Markets are incomplete, and households cannot borrow beyond the constraint b. Households may also receive a government transfer, $g_{i,t}$, financed by the revenue from carbon taxation. Aggregate consumption, labour and capital supply are given by summing individual household contributions.

$$C_t = \sum_{i=1}^{n} c_{i,t} \quad L_t = \sum_{i=1}^{n} l_{i,t} h_{i,t} \quad K_t = \sum_{i=1}^{n} k_{i,t}. \tag{2}$$

3.2 *Production*

The product market is competitive, where representative firms solve a static problem each period by choosing how much capital, K_t, labour, L_t, and fossil energy, E_t, to use in order to maximize profits.

$$\max_{K_t,L_t,E_t} \quad (1 - D(S_t))\tilde{F}(K_t, L_t, E_t) - r_t K_t - w_t L_t - (\kappa + \tau_t)E_t, \tag{3}$$

where $F\tilde{(.)}$ is production before damages are subtracted and $F(K_t, L_t, E_t, S_t) = (1 - D(S_t))\tilde{F}(K_t, L_t, E_t)$. Fossil energy can be produced at constant marginal cost, κ, and is in large enough supply such that there are no scarcity rents. While scarcity is a feature of oil and gas fuels, coal is in virtual infinite supply from the perspective of the intended model horizon. As firms are small they do not recognize the contribution of their own emissions to climate change. However, a regulator can implement a tax, τ_t, in order to impact their energy use. The climate externality manifests itself in the form of a reduction in aggregate production, $1 - D(S_t)$, where "damage", $D(S_t)$ is increasing in the atmospheric stock of carbon, S_t. In the model, carbon decreases production for a given set of inputs.

3.3 *Climate change*

The Greenhouse Effect arises from the growing stock of atmospheric carbon, S_t. As the stock of carbon grows, the energy flow out of the earth's atmosphere decreases and results in rising global temperatures. Economic activity contributes to the stock of carbon through the combustion of hydrocarbon energy, E_t. While there is a potential to model the complexity of the climate system, including multiple carbon reservoirs, feedback effects, etc., we employ a more concise statement of the climate system. The details of this system are outlined in the appendix.

As mentioned earlier, damage takes the form of a reduction in aggregate output. This is a large simplification of the negative impacts that a rising global mean temperature would have on human welfare. One could imagine other ways in which climate damage could be represented, such as direct loss to household utility, or an increase in the capital depreciation rate, however many IAMs, including Nordhaus' DICE model, assume a loss of aggregate output. For the sake of comparison to popular formulations of other IAMs, we choose to follow this assumption and implement the aggregate damage function proposed in Golosov et al. (2014).

$$1 - D(S_t) = \exp(-\theta_{k,t} S_t) \tag{4}$$

Climate change damage is also a source of aggregate risk, where the eventual realization of atmospheric carbon's potency as a GHG is a source of uncertainty faced by decision makers in the model. For simplicity, we assume there are two possible realizations of the aggregate shock, θ_k, which occurs in the future. θ_{high} occurs with the probability of π_{high} and denotes a high impact the climate externality, while θ_{low} occurs with probability $1 - \pi_{high}$.

4 Representative agent reference case

The solution to the model framework when markets are complete is equivalent to solving the model in the absence of income risk and borrowing constraints. If, in addition, global households are represented by an agent with mean wealth, the optimal tax has the familiar interpretation of the Pigouvian tax, which is set in order to equate the marginal private cost to the marginal social cost (in the case of a negative externality). With the ability to aggregate all agents in an economy to a single representative agent, it is also easy to define a social welfare function to be optimized: to maximize the representative agent's utility. Thus, we turn to the planning solution to identify the optimal level of emissions (which implies the optimal tax value) under complete markets.

$$\begin{aligned} \max_{C_t, K_{t+1}, E_t} \quad & \sum_{t=0}^{T} \beta^{t-1} \mathbf{E}[u(C_t)] \\ \text{s.t.} \quad & C_t + K_{t+1} = F(K_t, L_t, E_t, S_t) - \kappa E_t \end{aligned} \tag{5}$$

This problem delivers the first order condition

$$F_E - \kappa = \mathbf{E}_t \sum_{s=1}^{T} \beta^{s-1} \frac{u'(c_{t+s})}{u'(c_t)} F_S(K_{t+s}, L_{t+s}, E_{t+s}, S_{t+s}) S'_{t+s}, \tag{6}$$

where primes denote a function's first derivative with respect to E_t. The right hand side of this expression is often referred to as the social cost of carbon (SCC) and includes the damage associated with the negative externality from fossil fuel use, both in the current period and future periods through the persistence of the carbon pollutant. A regulator can implement the planning solution by setting the carbon tax equal to the SCC,which is equal to the difference between the marginal private benefit of fuel use (marginal product of energy F_E) and the marginal private cost, κ, at the social optimum fuel allocation[5]. The carbon revenue is rebated as a lump sum to the representative household.

5 Stylized model and calibration

In order to understand how household inequality may impact the setting of an optimal carbon policy, we propose a stylized version and calibration strategy of the dynamic model summarized above. The stylized model retains the features that are important for exploring the channels through which inequality and climate vulnerability matter. Dynamics coupled with uncertainty provide the channel through which the current poor are implicitly more vulnerable to climate risk.

5.1 *Period 1 as an endowment economy*

As an illustrative simplification from the Section 2 framework, we assume that there is no production in the first period, but rather households can consume and save from their initial endowment. Household inequality stems from the initial distribution of assets. An implication of there being no production is that there is no fossil fuel use in period 1, and thus the stock of carbon is only impacted *endogenously* by firms use of fuel in period 2. Production in period 2 yields factor prices from which households earn income in period 2.

This stylized model is summarized by the following household and firm problems, and their resulting equilibrium conditions.

$$\begin{aligned} \max_{c_{i,1},c_{i,2}} \quad & u(c_{i,1}) + \beta \mathbf{E}[u(c_{i,2})] \qquad (7) \\ \text{s.t.} \quad & c_{i,1} + k_{i,2} = \omega_i \\ & c_{i,2} = (1 + r_2 - \delta)k_{i,2} + w_2 h_{i,2} + g_{i,2} \\ & k_{i,2} \geq -b \end{aligned}$$

where ω_i is household i's initial endowment.

[5]See Golosov et al. (2014)

The resulting optimal savings condition for household i is given by:

$$
\begin{aligned}
& -u'(c_{1,i}) + \beta \mathbf{E}[R_2 u'(c_{2,i})] + \mu_i = 0 \qquad (8)\\
& \mu_i[k_{2,i} + (-b)] = 0\\
& \mu_i \geq 0
\end{aligned}
$$

Assuming CRRA utility, an unconstrained household i will save according to:

$$
(\omega - k_{2,i})^{\sigma} = \mathbf{E}\left[\frac{(w_2 h_{i,2} + R_2 k_{2,i} + g_{i,2})^{\sigma}}{\beta R_2}\right] \qquad (9)
$$

Assuming Cobb-Douglas production, period 2 factor prices and firm input demands are given by the solution to the firms problem as stated in the previous section:

$$
\begin{aligned}
r_t &= \alpha e^{-\theta_{t,k} S_t} K_t^{\alpha-1} L_t^{1-\alpha-\nu} E_t^{\nu} \qquad (10)\\
w_t &= (1-\alpha-\nu) e^{-\theta_{t,k} S_t} K_t^{\alpha} L_t^{-\alpha-\nu} E_t^{\nu} \qquad (11)\\
\kappa(1+\tau_t) &= \nu e^{-\theta_{t,k} S_t} K_t^{\alpha} L_t^{1-\alpha-\nu} E_t^{\nu-1} \qquad (12)
\end{aligned}
$$

From this we can see that fossil fuel demand is decreasing in τ , and thus can be set by the regulator to internalize the climate change externality. Also factor earnings are decreasing in the atmospheric stock of carbon.

5.2 *Generating inequality*

Household inequality in the stylized model arises from two sources: a random wealth endowment that places the recipient on the global wealth distribution; and an idiosyncratic labour productivity draw that adds to the initial endowment resources in the first period, as well determining the potential for future earnings. These sources of idiosyncratic uncertainty are potentially correlated, in that a household with a higher wealth endowment may be more likely to experience a high labour productivity shock in period 2. Labour is supplied inelastically, so a household's period 2 labour income is dependent on their period 2 productivity realization, and the prevailing aggregate wage.

Under this structure, the distribution of wealth is controlled by choosing a distribution for the initial wealth endowment. Income inequality consists of multiple states, which are meant to represent a household's position on the global income distribution. In general, there can be many income states, in order to meet more precise income inequality targets. Clearly, a realistic representation of global income inequality would require many income states - especially to represent the difference between those in poverty in the developing world and those living in poverty in a wealthy nation.

5.3 *Calibrating the stylized model*

In order to give the stylized model a quantitative grounding, we proceed by calibrating the model to reflect the global interaction of climate and the economy over two periods of fifty years each. The model has three broad categories for calibration: preferences and technology, carbon and climate, and household inequality.

Preferences and technology

We adopt fairly standard assumptions for preferences and technology from the macroeconomics literature, including CRRA utility, Cobb-Douglas production, and full depreciation. In the short-run, the degree of substitutability between capital-labour and energy should be relatively limited. However, the length of periods in the model allow assumptions that correspond to longer horizon characteristics of the production side. Factor shares, α and ν, are based on averages from historic data, with respective values 0.3 and 0.04 taken from Golosov et al. (2014). The final parameter on the firm side is the constant marginal cost of fossil fuel use, κ, which we calibrate endogenously to achieve the business-as-usual atmospheric stock of carbon estimates from the most recent IPCC report.

The choice of β is an important and controversial one in IAMs, as it determines the weight that current decision makers put on future generations, when the bulk of climate change is due to occur. The value of the optimal policy is very sensitive to the selection of this parameter (see e.g. Tol (2009), Saelen et al. (2008) and Anthoff et al. (2009b) for discussion). However, in the absence of heterogeneity across households in regards to β, it is not essential for understanding the question of *intra*-generational inequality.[6] For now we choose 0.98 as an annual rate, which is in a standard range for this parameter in the family of IAMs.

[6] It is perhaps worth discussing the role of heterogeneity in time preference as a theory of inequality and a means of generating realistic distributions of wealth in equilibrium (see for example Krusell and Smith (1998)) Clearly if households have varying preferences for future outcomes, this opens up another dimension for setting a one-size-fits-all carbon policy. We leave this to be explored in further work.

Carbon and climate

The carbon system specification of Golosov et al. (2014) requires three parameters that govern the response of the carbon stock over time, φ_L, φ_0, and φ. We set $\varphi_L = 0.2$ to reflect the fact that 20% of an emissions pulse will remain in the atmosphere forever. Likewise, φ governs the gradual decay of the portion of carbon in the atmosphere that is subject to natural absorption processes. Set to match the observation that this excess carbon has a half life of 300 years, $(1-\varphi)^{300/50} = 0.5$, this yields a value of about 0.109. Finally, φ_0 is identified by observing that roughly half of a given flow of emissions are removed from the atmosphere after 30 years. Thus $\varphi_0 = 0.4$ satisfies the following expression from equation 16: $1 - 0.5 = 0.2 + 0.8\varphi_0(1 - 0.11)^{3/5}$.

S_2 is the atmospheric carbon stock associated with IPCC predictions for business as usual (laissez faire equilibrium) $4°C$ increase in temperature by 2100. We can find this by using a formula from Arrhenius (1896), which relates an increase in the stock of carbon over pre-industrial levels to global mean temperature.[7]

$$4 = \Delta T = \lambda \frac{\ln \frac{S}{S_0}}{\ln 2} = 3\frac{\ln \frac{S}{600}}{\ln 2} \tag{13}$$

where λ denotes the *sensitivity* of temperature to atmospheric carbon concentration (or more precisely denotes the increase in temperature resulting from a doubling of pre-industrial atmospheric carbon concentration, which is here set to 3°C). This corresponds to an atmospheric carbon stock value of 1,500 gigatonnes of carbon (GtC). This is roughly 900 GtC in excess of pre-industrial levels. Thus 900 GtC becomes the calibration target for the business-as-usual (BAU) value of S_2 (after normalizing S_0 to 0). To find out how much carbon is emitted in the second period alone, we return to the IPCC BAU scenario which predicts roughly $2°C$ warming by 2050, and using the same method implies $S_1 = 350$ GtC. Taking the difference between the two periods' stocks implies that our laissez-faire economy has to produce $\phi E_2 = S_2 - S_1$, $E_2 = \frac{900-350}{0.49} \approx 1100GtC$.

The exponential functional form that climate damage takes requires the calibration of θ, which can be found by solving the relationship $1 - D(S) = exp(-\theta S_2)$. Following the calibration of Golosov et al. (2014), who also include uncertainty in their estimates, we choose $\{\theta_h, \theta_l\} = \{2.046 \cdot 10^{-4}, 1.060 \cdot 10^{-5}\}$. These values imply a loss to aggregate output of roughly 20% and 1% respectively, if S_2 reaches 900 GtC by 2100. Assigning probabilities to the two states, again we

[7]See Hassler et al. (2016) for further information.

follow the Golosov et al. (2014) calibration $\{\pi_h, \pi_l\} = \{0.068, 0.934\}$.

Household inequality

The final category for calibration is household inequality. As explained above, there are two sources of household heterogeneity, which arise from two sources of economic inequality. Agents in the model are assigned an initial wealth and labour productivity profile. Initial household wealth is distributed according to the wealth distribution in Davies et al. (2011). According to this study the level of wealth in our base year 2000 is 44,000 per adult (PPP), and the distribution is summarized below in 1.

Decile	1	2	3	4	5	6	7	8	9	10	Gini
World wealth share %	0.1	0.3	0.6	1.1	1.6	2.4	3.8	6.3	13.1	70.7	0.802

Table 1: Distribution of Wealth

Agents are also assigned a productivity state in the first period, which corresponds to their position in the income distribution. There are five productivity states calibrated according to the quintiles of the global income distribution (PPP) in Ortiz and Cummins (2011) and shown in the calibration Table 2 on page 14. we assume that whatever causes a household to be productive also causes them to be wealthy, such that the initial wealth endowment is distributed according to a household's position on the income distribution (and vice versa). Since the first period is an endowment economy, a household's first period productivity state determines two things: their belief about their future earnings (through the probability transition matrix) and the total size of their period 1 endowment. Thus, each household receives two endowments, one that represents their initial wealth holdings, and one that represents the labour income they earn during the first 50-year period. As income is a flow, we calculate the income endowment by taking the level of income (PPP) in the base year, and grow it at the growth rate of world GDP over the first period and then sum all years. We then take this total amount and divide it in proportion to a quintile's share of total income. Each member within a quintile receives an equal amount of that quintile's share.

6 Carbon tax experiment

As an exercise to examine the impact of a carbon tax over the distribution of households, we evaluate the stylized model over a grid of tax values, and examine the response of households

Parameter	Value	Description	Source
Preferences			
β	0.98	Annual discount factors	*Macro literature*
σ	1.5	Co-efficient or relative risk aversion	Author choice
Technology			
α	0.3	Capital's value share of output	*Macro literature*
ν	0.04	Fossil energy's value share of output	(Golosov et al., 2014)
δ	1	Full capital depreciation	Author choice
b	0	Household borrowing limit	Author choice
Carbon and climate			
θ_l	$1.9341 \cdot 10^{-5}$	Climate damage elasticity in low state	(Golosov et al., 2014)
θ_h	$2.3780 \cdot 10^{-4}$	Climate damage elasticity in high state	—"—
$[\pi_l, \pi_h]$	[0.932, 0.068]	Probabilities of aggregate states	—"—
φ_L, φ_0, φ	0.2, 0.4, 0.109	carbon depreciation rates	
Inequality			
Income quintiles	[0.827, 0.117, 0.023, 0.019, 0.014]	Share of global income	Ortiz and Cummins (2011)

Table 2: Parameters Calibrated Exogenously

across the wealth distribution, the idea being that the characteristics of an individual household will lead to varying welfare impacts, and thus a most-preferred tax value. As the first period is an endowment economy, the carbon tax is only levied in the second period when production occurs. However the value of the tax is "negotiated" in the first period. Although pessimistic, it is perhaps not an unrealistic assumption that a globally coordinated tax needs to be set in advance of the period in which it becomes active. Choosing the carbon policy in advance implies that welfare analysis is from the perspective of period 1. Thus a household's favourite tax is chosen *ex ante* according to its beliefs about what will happen in the future.

Given the degree of inequality in the world, there is substantial opportunity to increase welfare through redistribution strategies, or pursuing "double dividend" tax relief. In the absence of distortionary taxes in the model, we opt for lump sum redistribution of the carbon tax revenue. There are many possible ways to share the tax revenue, and this will have a large impact on the identity of an agent's most preferred tax. For this exercise, we explore several approaches for handling the tax revenue. In the first case, we discard the tax revenue in order to isolate the mechanisms associated with the carbon tax's impact on capital and labour income. Discarding revenue is clearly suboptimal; however, it reveals a few channels through which the carbon tax can influence a household's welfare and thus most preferred policy (and the implied carbon concentration).

The second approach is to rebate the tax according to two different rules, uniform and regressive. The response of a household's policy preference to the way in which revenue is rebated highlights the importance of redistribution and risk mitigation in the face of incomplete insurance markets. Clearly a uniform redistribution rule is a very progressive use of the carbon tax revenue, and the range of most preferred taxes reflects this. The regressive rule rebates the revenue in proportion to a household's second period productivity realization. Thus a high income realization in the second period also means a high carbon rebate.

Another key assumption in the incomplete markets framework is the persistence of the income process. If the income process is serially correlated, then a household's current position gives information about their future income as well. While there is likely income persistence across generations, especially on the global income distribution, we use an i.i.d income process for the starting point in my analysis. Thus a household's current income productivity does not carry any information about tomorrow's productivity realization, and a household's policy preference depends only upon its cash on hand in period 1. In addition to i.i.d income processes, we will explore the implications of income persistence later in this section.

All welfare impacts are calculated as conditional welfare changes and measured in consumption-equivalent variation. Welfare impacts are conditional on agent characteristics included in the model, i.e. wealth, k and labour productivity, h.[8] $\lambda_i(k,h)$ solves the following equation, and is interpreted as the change in consumption across all states and periods that leaves household i, with wealth k and productivity h, indifferent between the unregulated equilibrium and living through the equilibrium induced by the policy change.

$$\sum_{t=1}^{2} \beta^{t-1} \mathbf{E}[u((1+\lambda_i(k,h))c^*_{i,t})] = \sum_{t=1}^{2} \beta^{t-1} \mathbf{E}[u(\tilde{c}_{i,t})] \tag{14}$$

where $\{c^*_{i,t}\}$ is household i's sequence of consumption under the equilibrium without mitigation and $\{\tilde{c}_{i,t}\}$ is household i's consumption sequence under a given climate policy.

6.1 *Discarded revenue*

We begin with an experiment where the carbon tax revenue is discarded. Following the calibration described above reveals that a standard calibration of climate damage is insufficient to make any agent better off. Figure 1 shows the difference between gross output and output net of carbon tax revenue. From the gross output curve, we see that the carbon tax increases the availability of

[8] See Floden (2001) for discussion.

aggregate resources over a range of the instrument. The difference between the two curves is the revenue raised by the regulator from levying the carbon tax on fossil fuel use.

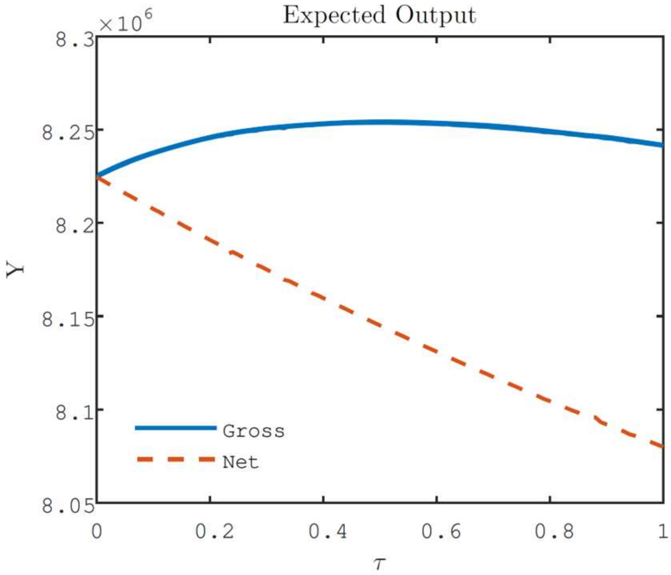

Figure 1: Output response to carbon tax

At the baseline calibration for climate sensitivity, carbon taxation is welfare decreasing for all agent types, if the revenue is discarded. In order to proceed, we make an adjustment to the damage parametrization, which will become a point of comparison for both the case where tax revenue is discarded, as well as the cases where revenue is returned. The extent of damage from climate change is one of the most uncertain aspects of calibration in IAMs. If the climate is more sensitive than the standard calibration, then temperature will rise more quickly, and damage will be more severe. In an alternative high climate sensitivity calibration, we assume that damage to production is twice as bad in expectation as in the previous calibration. Here 10% of production will be lost when atmospheric carbon reaches 1500 GtC by 2100, rather than 5%. To do this we leave the elasticity of damage in the high damage state unchanged at $\theta_h = 1.9341 * 10^{-5}$, but increase the elasticity of damage in the low state to $\theta_l = 6.0335 * 10^{-5}$. The high and low aggregate state probabilities remain unchanged. The big implication of increasing the elasticity of damage is that the benefits from reducing emissions outweigh the costs, even when the tax revenue is discarded. This is a way of understanding how the carbon tax affects households in the absence of redistribution. Taking the carbon tax rebate out of the policy means that household welfare can only be influenced through the tax's impact on labour and capital earnings.

The first case for this experiment is one where the state of the climate does not have implications for the idiosyncratic risk. That is, the pay-offs and transition probabilities in the idiosyncratic states are the same whether the aggregate state is good or bad. In addition there is no income persistence across periods, as agents face i.i.d probability. Thus an agent in period 1 is equally likely of transitioning to one of the five income states in period 2. While perhaps unrealistic in a global inequality context, an i.i.d probability transition matrix is attractive for my initial analysis, as it ensures that households have identical income risk profiles. Thus households differ only on the amount of resources available to them in the endowment period. We leave the assessment of persistent income states for sensitivity analysis. Figure 2 reveals that there is little difference between household preferences for carbon taxation. Since income earned over 50 periods is much larger than initial wealth, total cash on hand reflects a household's position in the initial income quintiles.

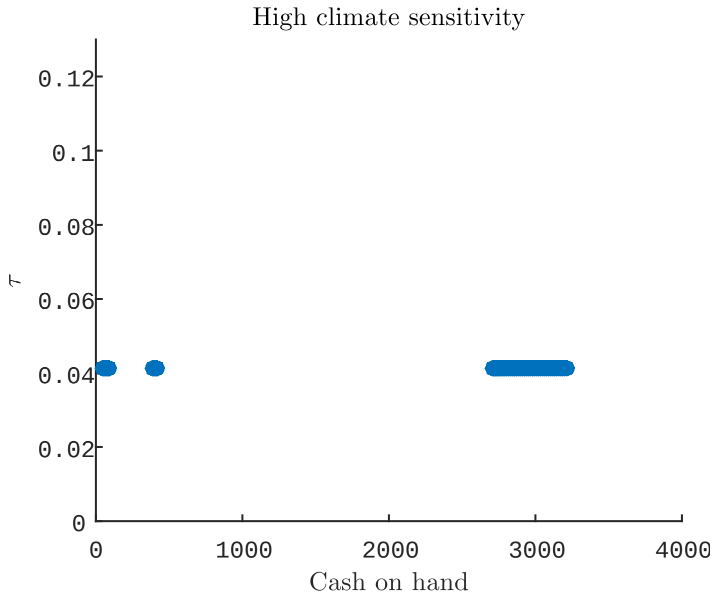

Figure 2: HH Wealth Endowment vs Most Preferred Carbon Tax - no rebate

Note: This figure shows the relationship between household cash on hand in the initial period and its policy preference for the following period. In this scenario, the following assumptions hold: the government discards the tax revenue; the climate is more sensitive than under the standard assumptions; and income risk is not correlated with aggregate climate risk. The pattern of household policy preference shows very little dispersion by wealth.

The reason for this result comes from the symmetry in how the sources of household earnings are impacted by climate change damage in the model. With full depreciation and Cobb-Douglas production, the proportional change in the factor earnings are quantitatively very similar in this case.[9] This symmetry means that households who receive their earnings entirely from labour, or entirely from capital, benefit from the carbon tax similarly.

If, on the other hand, household idiosyncratic risk is positively correlated with the aggregate climate state, this symmetry between earnings sources breaks down. Following the notion that climate impacts will be unequally distributed across the population, we explore the implications of

[9]In addition, if utility was logarithmic there would be no savings adjustment at all by households, even in the case below where we assume idiosyncratic risk is positively correlated with aggregate climate risk.

adverse shocks hitting a subset of the population; the idea being that low productivity households will be impacted more by climate change than high productivity households. Some examples of how this might occur is from the evidence of temperature on labour productivity. Dell et al. (2012) discuss the existing empirical evidence noting that sectors which involve outdoor labour, such as agriculture, mining, construction, forestry, etc. see drops in productivity during high temperature weather. Agriculture is arguably the most susceptible to climate change impacts, and the global agricultural labour force is largely concentrated in low income countries and amongst low earners.

From the equity premium literature Mankiw (1986) shows that when asset markets are incomplete, the concentration of ex post adverse shocks can increase the ex ante value of existing market assets. This logic translates into the climate change framework when idiosyncratic productivity is correlated with the aggregate climate state. To explore this we introduce a mean-preserving spread to the idiosyncratic productivity states, when the aggregate climate state is bad. Thus, the volatility of labour productivity increases when climate damage is most severe. Since all households are equally likely to be subject to these shocks in the future, it does not change their expected labour income, only its volatility. Their labour productivity states are thus:

$$\begin{pmatrix} h_1 - \mu & h_2 - \mu & h_3 - \mu & h_4 + \mu & h_5 + 2\mu \end{pmatrix} \tag{15}$$

where μ is a parameter that makes the productivity worse for the three lowest quintiles, but doesn't alter the expected value of tomorrow's income productivity realization. In this case, the uncertainty of labour income increases putting additional pressure on poor constrained households who rely completely on their future productivity realization for period 2 welfare. We choose a μ equal to 0.01, which under my income state calibration results in a roughly 70% loss in productivity for the lowest quintile should the climate realization be the high damage state. From an aggregate perspective this may seem like a high number. However, recent studies on disaggregated impacts, such as Krusell and Smith Jr (2015), find damage impacts similar to these magnitudes even in scenarios which correspond to aggregate global damages that are in line with the low damage aggregate state. Figure 3 reveals a relationship between a household's most preferred tax and its wealth endowment.

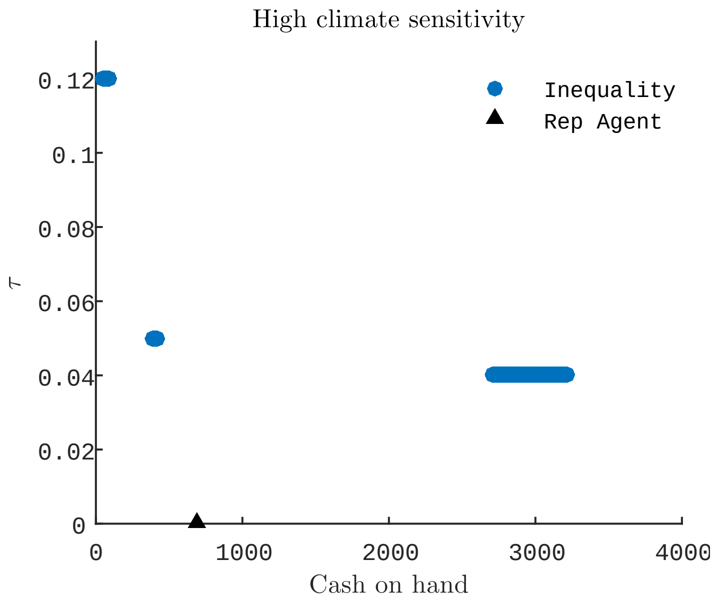

Figure 3: HH Wealth Endowment vs Most Preferred Carbon Tax - no rebate, correlated risk

Note: This figure shows the relationship between household cash on hand in the initial period and its policy preference for the following period. In this scenario, the following assumptions hold: the government discards the tax revenue; the climate is more sensitive than under the standard assumptions; and income risk is correlated with aggregate climate risk. The pattern of household policy preference now shows significant dispersion by wealth. The representative agent comparison for this experiment is included, where insurance markets are complete (no idiosyncratic income risk), and all households have mean wealth.

Poor constrained households prefer a tax more than twice as large as their wealthier unconstrained counterparts. This result arises from constrained households having greater exposure to climate risk. Agents who rely entirely upon labour income benefit from stronger action on climate change, as cutting emissions reduces losses associated with the worst potential outcomes. Agents with private savings will not be hurt as badly in these realizations, as they will have additional resources on hand for adaptation regardless of their labour productivity state. Amongst unconstrained households the relative composition of earnings determines their most preferred tax, with the fourth income quintile still receiving a large enough proportion of their earnings from labour to prefer a higher carbon tax than the wealthier quintile above them.

There are, however, additional general equilibrium considerations for wealthy household tax preference. Figure 4 charts household tax preference against their wealth endowment, when only considering the portion of their earnings from capital. This reveals a reversal of the pattern under total earnings. Here wealthier households prefer a *higher* tax. The reason for this is that carbon taxation reduces savings more quickly amongst poorer households. This reduction in savings benefits wealthier households through higher returns on their own savings, which they are not inclined to adjust as quickly in the face of increased carbon taxation.

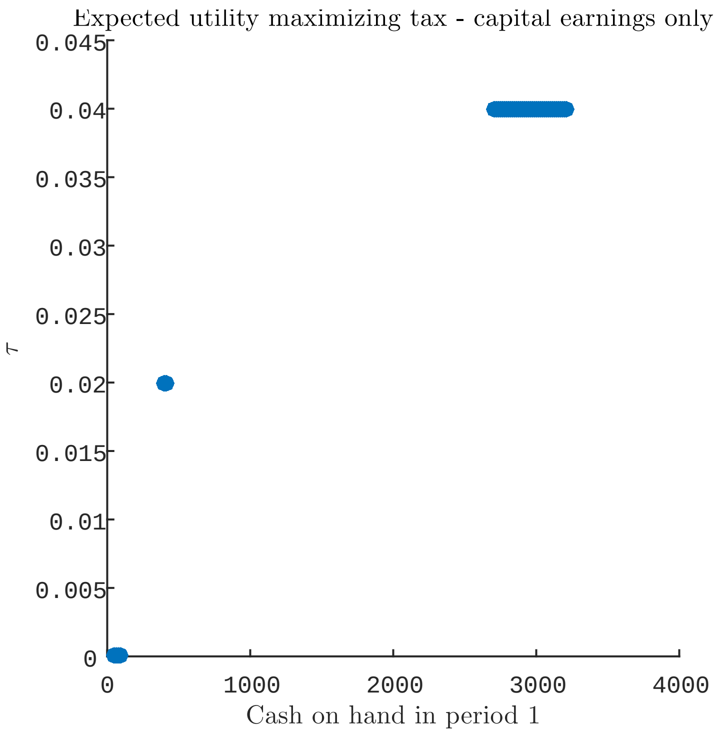

Figure 4: HH Wealth Endowment vs Most Preferred Carbon Tax - capital earnings only

Note: This figure shows the relationship between household cash on hand in the initial period and its policy preference for the following period when only taking into account capital earnings. In this scenario, the following assumptions hold: the government discards the tax revenue; the climate is more sensitive than under the standard assumptions; and income risk is correlated with aggregate climate risk.

This general equilibrium effect only slightly attenuates the income composition effect, and on the whole carbon tax preference is decreasing in wealth.

6.2 *Uniform rebate*

In this section we present the results from the same tax experiment as above, except instead of discarding tax revenue it is returned in a uniform lump sum to all households, $g_{i,2} = \frac{\tau E_2}{n}$. The income process remains as i.i.d and the relationship between the idiosyncratic income risk and aggregate climate state is the same as detailed above; that is, the mean-preserving spread detailed in object 15 occurs if the aggregate climate risk has a bad realization. This experiment is characterized by a large degree of redistribution, where constrained and low wealth households anticipate that the rebate will significantly supplement their expected future income. Additionally, the uniform rebate is predictable and independent of the idiosyncratic income risk (though still dependent on aggregate risk). Figure 5 shows the relationship between a household's cash on hand in period 1 and their most preferred tax.

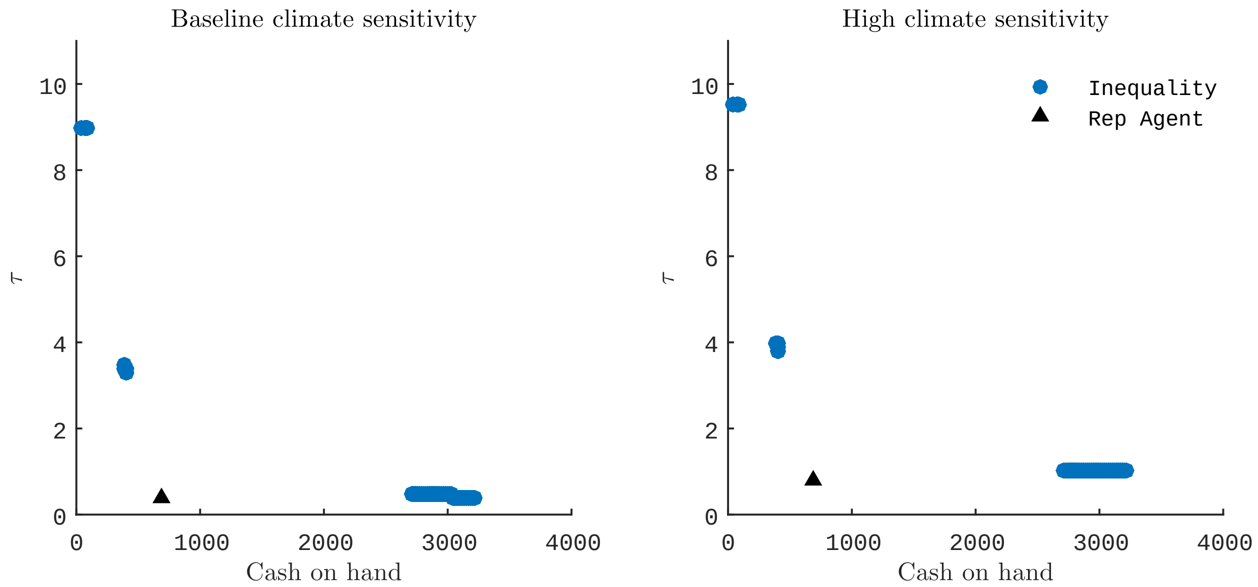

Figure 5: HH Wealth Endowment vs Most Preferred Carbon Tax - uniform rebate

Note: This figure shows the relationship between household cash on hand in initial period and its policy preference for the following period. In this scenario, the following assumptions hold: the government rebates tax revenue as an equal lump sum to all households; and income risk is correlated with aggregate climate risk. The left panel uses the standard climate sensitivity parameterization, and the right uses the higher sensitivity assumption. The representative agent comparison for this experiment is included, where insurance markets are complete (no idiosyncratic income risk), and all households have mean wealth.

Clearly the degree of redistribution is very important for low asset households, and this is reflected in the very high level of their most preferred tax instrument. Under the baseline climate sensitivity, the poorest households prefer a tax instrument of 900% of the fuel input cost. The wealthiest households prefer a tax instrument that is 40-50%. Increasing climate sensitivity reveals roughly a level shift up of the most preferred tax, reflecting the impact of climate risk specifically on the most preferred instrument. This indicates that the high tax rates reflect the strong preference for redistribution and income certainty provided by the uniform rebate.

6.3 *Regressive rebate*

As an alternative to the highly progressive use of the carbon tax revenue in a uniform rebate, we explore returning the carbon tax revenue in a regressive way. In this case, the revenue is returned in proportion to a household's period 2 income productivity draw, $g_{i,2} = \frac{h_{i,2}}{\bar{h}} \frac{\tau E_2}{n}$, where $\bar{h}$ is the mean of all income states. There are several implications of this change from the uniform rule. First, while the ex ante *expected* rebate is the same as the uniform rebate, the ex post realization of the rebate is now tied to the idiosyncratic risk of household productivity. This eliminates the predictability of the rebate, and as can be seen in Figure 6, greatly reduces the value of the policy for all households. Under the regressive rebate rule, the poorest households prefer a tax instrument equal to about 110% of the fuel input cost - almost an order of magnitude smaller than under the uniform rebate. Also, interestingly, the wealthiest households would rather not have a carbon tax at all, if the tax revenue is rebated according to this regressive rule. The contrast between these two rules illustrates the cost that risk imposes on all households. The certainty of the uniform rebate is much more valuable for all households, and especially poor households.

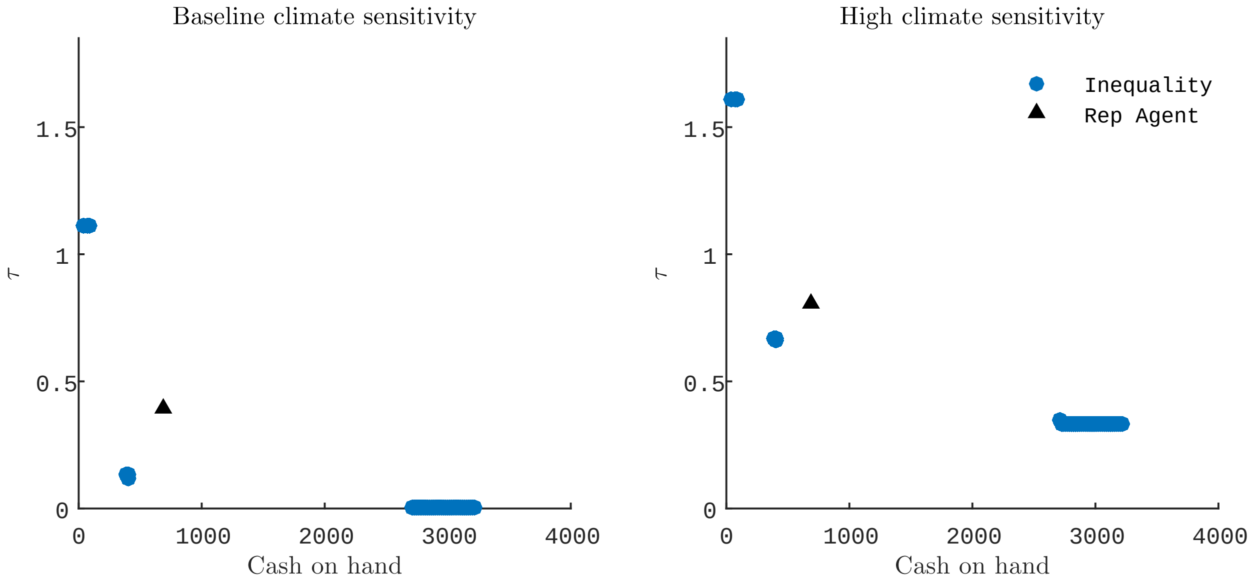

Figure 6: HH Wealth Endowment vs Most Preferred Carbon Tax - regressive rebate

Note: This figure shows the relationship between household cash on hand in the initial period and its policy preference for the following period. In this scenario, the following assumptions hold: the government rebates tax revenue in proportion to their period 2 productivity draw; and income risk is correlated with aggregate climate risk. The left panel uses the standard climate sensitivity parameterization, and the right uses the higher sensitivity assumption. The representative agent comparison for this experiment is included, where insurance markets are complete (no idiosyncratic income risk), and all households have mean wealth.

Increasing the climate sensitivity results in an upward shift in tax level preference, reflecting climate damage contribution to the social cost of carbon. At the higher climate sensitivity, the wealthiest households now prefer a positive value of the carbon tax. In level terms the tax rate preference increases more for the poor than wealthy if the climate is more sensitive.

6.4 Income persistence

In the earlier experiments the income process was not persistent, and thus a household's current position on the income distribution did not predict their future earnings. This was a convenient assumption in order to isolate the impact of cash on hand, specifically. Introducing some serial correlation to the income process means a few things. First, the amount of idiosyncratic risk decreases reducing the need for insurance. Second, a household's income draw in the first period becomes more informative about the value of the future rebate, especially when the rebate is conditioned on the future realization, as in the *regressive* rule. In the following experiments we modify the income process to include some serial correlation. Specifically, we double the probability that a household remains in their current productivity bracket (from 20% to 40%).

In the two rebate scenarios this has the following effects. First, in the uniform rebate the redistribution motive is strengthened, resulting in a higher desired carbon tax instrument by the least wealthy households. With income persistence the poorest households have a lower expected labour income in the future; thus the uniform rebate becomes an even larger share of their expected total income. Likewise, the wealthiest households have more confidence in their future labour earnings. Thus the uniform rebate is worth much less to them, and reflected in the lower desired instrument level. However, income persistence does not dramatically alter the findings under the i.i.d experiments. Increasing the amount of serial correlation in the income process will lower the value of the carbon tax and rebate scheme as implicit insurance, because the amount of income risk is decreasing. This will tend to lower the most preferred tax for all households. Figure 7 shows the new, most preferred tax relationship to cash on hand in period 1, with a uniform rebate scheme.

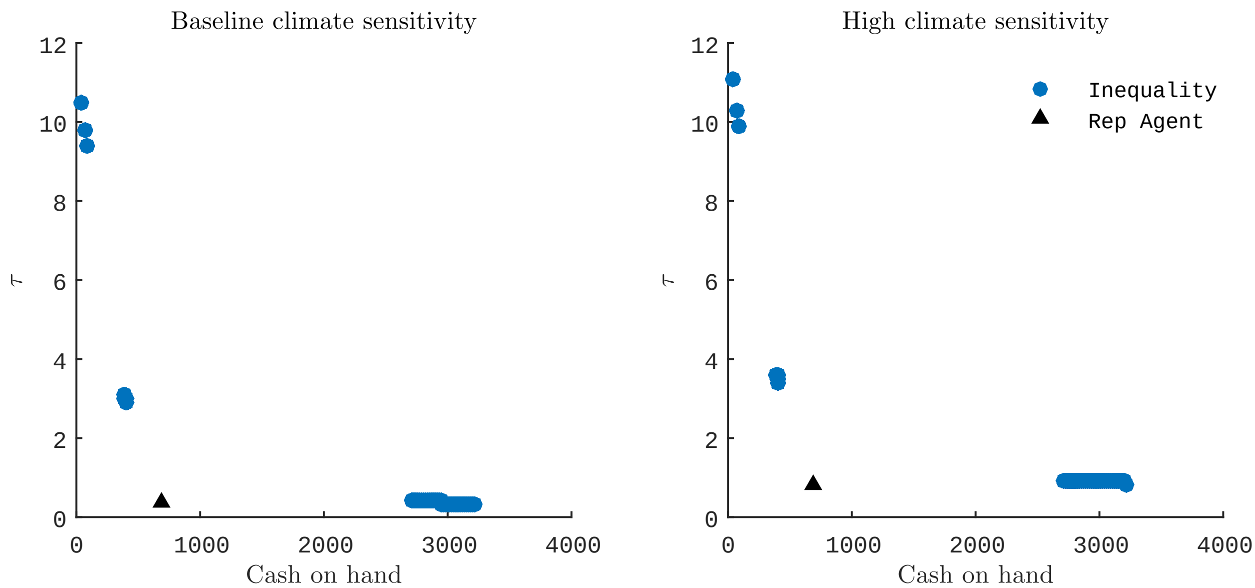

Figure 7: HH Wealth Endowment vs Most Preferred Carbon Tax - uniform rebate - persistent income

Note: This figure shows the relationship between household cash on hand in the initial period and its policy preference for the following period. In this scenario, the following assumptions hold: the government transfers tax revenue equally to households as a lump sum; income risk is correlated with aggregate climate risk; and the income process is serially correlated. The left panel uses the standard climate sensitivity parameterization, and the right uses the higher sensitivity assumption. The representative agent comparison for this experiment is included, where insurance markets are complete (no idiosyncratic income risk), and all households have mean wealth.

7 Conclusion and discussion

Currently, models of climate and the economy answer normative questions about optimal carbon taxation, under assumptions of complete markets and representative agents. Relaxing these two assumptions allows a better understanding of how implicit vulnerability of poor households and distributional impacts can shape the optimal policy problem. Modifying a simple integrated assessment model, with a standard incomplete markets framework, is a first step in incorporating concerns of global household inequality in a familiar policy evaluation framework for addressing climate change.

A common theme in the literature on incomplete markets is the role of public policy as implicit insurance. In the absence of comprehensive risk markets, policy makers can improve welfare by implementing various policies, e.g. progressive income taxation and public pension plans. This study shows that carbon taxation can fill a similar role in an integrated assessment model setting. A carbon policy fulfils this role in several ways. First, the tax reduces the use of fossil fuel, and thus mitigates the severity of climate damage, especially in extreme realizations of aggregate risk. In the model there are two sources of risk for which agents self-insure through precautionary savings; idiosyncratic productivity and aggregate climate risk. Lower wealth agents make a relatively costly trade-off by reducing current consumption to insure against both lower labour earnings and a bad realization for the climate state. As emissions negatively impact aggregate prices, the carbon policy can both improve tomorrow's expected earnings and reduce the volatility of tomorrow's consumption. Furthermore, if idiosyncratic productivity outcomes are correlated with the aggregate climate state, such that household productivity is more volatile in a bad climate state, then the tax becomes more important for all households, and poor households in particular. Secondly, the carbon policy presents an opportunity to increase the gross resources available by internalizing the climate change externality. The way these additional resources are distributed amongst the population can have substantial welfare implications, particularly for constrained households who are unable to self-insure.

The most interesting result from this experiment is the heterogeneity in tax preference in the absence of redistribution. Household income arises from two sources, capital and labour. Since households differ in their endowment, the relative importance of the source of their income can introduce asymmetries in their tax preference. When idiosyncratic productivity shocks are correlated with the aggregate climate state, households face asymmetric risk to the two components of their income. Households which rely more heavily on their labour earnings, i.e. the poor, will prefer a tax that improves both the expected value and volatility of labour earnings. In addition, agents who have substantial private savings will face less volatility in their utility, implying that risk *per se* is more harmful to poor households. For these reasons we observe a result where tax level preference decreases with wealth.

The magnitude of differences in carbon tax preferences across the distribution of households is largely dominated by concerns over the direction of transfers. This holds true even under consideration of high climate damage. The degree of economic vulnerability that arises in the standard incomplete market setting places a large emphasis on how the transfers are directed, as well as their predictability. The role that carbon policy plays as a form of public insurance, will be a significant part in determining the identity of a global tax agreement in a setting of incomplete markets and substantial household inequality.

8 Appendix

8.1 Carbon cycle

The framework abstracts from temperature instead focuses on carbon as the key climate state variable. Golosov et al. (2014) propose the following reduced-form carbon depreciation function, which relates facts about the persistence of carbon emissions in the atmosphere to how much of a marginal impulse of emissions remains in the atmosphere after a length of s periods.

$$1 - d(s) = \varphi_L + (1 - \varphi_L)\varphi_0(1 - \varphi)^s \tag{16}$$

where φ_L is the share of E_t that remains in the atmosphere forever, and the remaining parameters are calibrated to account for facts about the life-cycle of carbon in the atmosphere. Thus there are two components of $S_t = S_{perm,t} + S_{depr,t}$ at any point in time, a permanent component $S_{perm,t} = S_{perm,t-1} + \varphi_L E_t$, and a component that depreciates over time, $S_{depr,t} = \varphi S_{depr,t-1} + \varphi_0(1 - \varphi_L)E_t$.

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