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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. In contrast to the representative agent framework, we find that 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. We find the carbon tax 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, even in the absence of redistribution. Taking into account the risk channel, we find an optimal tax value four times larger than standard estimates from representative agent models.

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

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1 Introduction

To date, most models of climate and the economy have calculated optimal carbon policy under the assumption of complete markets and/or 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 a more realistic setting, we relax these assumptions from the integrated assessment modelling literature, and introduce a standard incomplete markets framework, which allows us to replicate the world income distribution. Thus, in addition to an uncertain global climate state, households also face idiosyncratic productivity shocks for which they can not insure away.

Introducing a realistic distribution of households from 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 redistribution. Moving beyond the limits of the representative agent framework, we identify two additional channels through which carbon taxation impacts household welfare. The first channel, which is common to both the complete and incomplete markets setting, is that the carbon policy works to internalize the climate externality and increase the level of available resources. Second, the revenue of the carbon tax creates an opportunity to redistribute resources to those who benefit from them more. And finally, the policy intervention reduces the risk of extreme loss as a result of both catastrophic climate outcomes and household income vulnerability.

As a result of these additional channels, we find that the optimal tax chosen by a utilitarian regulator is significantly higher than in a representative agent framework. Moreover, we find that even absent of re-distributive motives, the preferred optimal tax is four times larger than other standard estimates in the literature. This illustrates that the cost of risk is a strong motivation for public action on climate change.

The importance of the insurance channel becomes even greater when we consider the relationship between climate risk and individual vulnerability. Specifically, when aggregate climate risk and individual income risk are correlated —the most empirically plausible case —such that inequality grows when climate damage is severe, the optimal tax value rises. This is largely driven by the lower tail of the distribution where vulnerable households, who are not able to move adaptation resources to the future, want even stronger action on climate change.

2 Background

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.

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 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 most 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.

A growing empirical literature on the impacts of climate change identifies significant distributional considerations. Diffenbaugh and Burke (2019) show a connection between climate change and growing global inequality, arising from the impact of temperature on growth. They show that global warming has likely slowed growth in poorer countries and reduced the rate of convergence that would have prevailed had temperatures remained steady. Islam and Winkel (2017) provide a comprehensive accounting of the channels through which climate change impacts inequality, noting that the poor are more exposed, susceptible and less able to cope with climate change.

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

[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)

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

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. 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. Likewise, Carleton and Hsiang (2016) detail the impact of weather and temperature on social outcomes.

2.1 Related literature

In terms of modelling, 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.

Our 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 equilibrium 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, the aggregate stock of capital, and their own income prospects. 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:

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

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

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

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_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. All tax revenue is rebated uniformly to the households within the same period[4]. The climate externality manifests itself in the form

[4]We follow the literature and assume a frictionless global regulator. In truth, coordinated global action on both

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[5], 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 $1 - \pi_{high}$.

The current framework is concerned with the standard definition of risk as opposed to radical uncertainty. We intend for risk and uncertainty to be used interchangeably, where the joint distribution of both aggregate climate risk and idiosyncratic income risk are well understood by households with rational expectations. This is admittedly a strong assumption given the nature of

carbon price setting and revenue redistribution is likely (very) costly.

[5] 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.

climate change risk. [6]

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 expected lifetime 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[7]. The carbon revenue is rebated as a lump sum to the representative household.

[6] See O'Hara (2009) and Monasterolo et al. (2019) for a treatment of a more inclusive definition of uncertainty.

[7] See Golosov et al. (2014)

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 emissions are exogenous 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.

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

where Ω_i is household i's initial endowment of cash on hand.

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

$$\begin{aligned}
&-u'(c_{1,i}) + \beta \mathbf{E}[(1 + r_2 - \delta)u'(c_{2,i})] + \mu_i = 0 \\
&\mu_i[k_{2,i} + (-b)] = 0 \\
&\mu_i \geq 0
\end{aligned} \tag{8}$$

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

$$(\omega - k_{2,i})^{\sigma} = \mathbf{E}\left[\frac{(w_2 h_{i,2} + (1 + r_2 - \delta)k_{2,i} + g_{i,2})^{\sigma}}{\beta(1 + r_2 - \delta)}\right] \tag{9}$$

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:

$$r_t = \alpha e^{-\theta_{t,k} S_t} K_t^{\alpha-1} L_t^{1-\alpha-\nu} E_t^{\nu} \tag{10}$$

$$w_t = (1 - \alpha - \nu) e^{-\theta_{t,k} S_t} K_t^{\alpha} L_t^{-\alpha-\nu} E_t^{\nu} \tag{11}$$

$$\kappa(1 + \tau_t) = \nu e^{-\theta_{t,k} S_t} K_t^{\alpha} L_t^{1-\alpha-\nu} E_t^{\nu-1} \tag{12}$$

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.

Our model follows most of the incomplete markets literature in using idiosyncratic labour productivity shocks as the source of heterogeneity. More recent studies[8] have focused on the role of heterogeneous returns to savings as a source of income and wealth heterogeneity, given empirical studies that brought forth its relevance[9]. In such an environment, the risk channel would potentially yield even more carbon tax preference heterogeneity, arising from the fact that self-insurance would be more expensive for poorer agents given their lower rates of return. We anticipate that in such a framework, the role of carbon taxation as public insurance would be even stronger.

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 economy grows at an annualized rate of 1.6% across periods.

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.[10] We choose 0.985 as an annual rate, which is in a

[8]See Hubmer et al. (2020)

[9]see Jordà et al. (2019)

[10]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

standard range for this parameter in the family of IAMs.

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 22: $1 - 0.5 = 0.2 + 0.8\varphi_0(1-0.11)^{3/5}$.

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.[11]

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

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 $\phi E_2 = S_2 - S_1$, $E_2 = \frac{900-350}{0.49} \approx 1100GtC$.[12] In our baseline calibration, a marginal cost of fuel, κ, of $\$168/tC$ is associated with this target stock of atmospheric carbon.[13]

carbon policy. We leave this to be explored in further work.

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

[12]See Appendix for calculation of how much of a given emissions impulse remains in the atmosphere for our model period length.

[13]This value falls between the price of coal at $\$103.35/tC$ and oil $\$606.5/tC$ referenced in Hassler et al. (2016)

The exponential functional form that climate damage takes requires the calibration of θ, which can be found by solving the relationship $1 - D(S) = exp(-\theta S_2)$. In order to implement a damage calibration which implies, in expectation, a 5% aggregate economic loss at business-as-usual atmospheric carbon levels[14], we modify the calibration of Golosov et al. (2014), who also include uncertainty in their estimates[15]. We choose $\{\theta_h, \theta_l\} = \{2.378 \cdot 10^{-4}, 4.379 \cdot 10^{-5}\}$, which imply a loss to aggregate output of roughly 20% and 3.8% respectively, if S_2 reaches 900 GtC by 2100. Assigning probabilities to the two states, we follow the Golosov et al. (2014) calibration, which assigns probabilities to the high and low states, $\{\pi_h, \pi_l\} = \{0.068, 0.932\}$.

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 Gini coefficient on global wealth is 0.80.

Globally, many studies show that income inequality has been decreasing, due to catch-up dynamics from emerging economies. Lakner and Milanovic (2016) point out that between the 1980s and 2000s, this is not actually the case and that inequality did not change when taking into account the differences between countries, as well as, the inequality between households, within countries, which offset the former. Hellebrandt and Mauro (2015) look into the same time period and extend the analysis into 2035. They confirm the results, but show that since the 2000s, the decrease in income inequality between countries more than compensates the increase within, and therefore predict a decrease in global income inequality.

We calibrate our model to replicate the global inequality reported by Hellebrandt and Mauro (2015) and make the evolution of inequality throughout our analysis consistent with the authors' findings. Agents are assigned a productivity state in the first period, which corresponds to their position in the income distribution. These productivity states represent the inequality to prevail in 2025, the midpoint of our first model period. We construct this distribution by combining the 2015 observation and 2035 forecast on global household income inequality. We then extrapolate

[14] An estimate similar to DICE in Nordhaus (2008) and within the range presented by the IPCC in Solomon et al. (2007)

[15] For completeness, we include our optimal tax results with Golosov et al. (2014) damage calibration in the Appendix.

the fall in inequality according to the trends observed from the first period. This corresponds to a fall of 9 percentage points in the global income Gini, from 0.63 to 0.54 in 2075.

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. 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 quantile's share of total income. Each member within a quantile receives an equal amount of that quantile's share.

Parameter	Value	Description	Source
Preferences			
β	0.985	Annual discount factors	*Macro literature*
σ	2	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	$4.3790 \cdot 10^{-5}$	Climate damage elasticity in low state	(Golosov et al., 2014)
θ_h	$2.3780 \cdot 10^{-4}$	Climate damage elasticity in high state	(Golosov et al., 2014)
$[\pi_l, \pi_h]$	[0.932, 0.068]	Probabilities of aggregate states	(Golosov et al., 2014)
φ_L, φ_0, φ	0.2, 0.4, 0.109	Carbon depreciation rates	
Inequality			
Income inequality	0.63 (in 2025) and 0.54 (in 2075)	Global income inequality, Gini projections	Hellebrandt and Mauro (2015)
Wealth inequality	0.80	Global wealth Gini (2000)	Davies et al. (2011)

Table 1: Parameters Calibrated Exogenously

Social welfare function

Aggregate welfare analysis, and thus the identity of the optimal carbon tax is straightforward in the representative agent case. However, when including inequality this calculation becomes more nuanced and requires one to take a stance on the valuation of an individual household's contribution to the aggregate welfare response. One way of doing so is to write down the utilitarian welfare function, which is a uniformly weighted aggregation of each household's lifetime utility. The utilitarian welfare gain is measured as the life-time consumption equivalent "premium", ω_U, of all households living through the proposed carbon tax policy:

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

Where $\{c^*_{i,t}\}$, is the consumption sequence experienced by household i under a carbon tax policy, and $\{\tilde{c}_{i,t}\}$ is the consumption sequence under the unregulated equilibrium. The utilitarian optimal carbon tax policy is the level that maximizes ω_U. All welfare analysis is performed *ex ante* from the perspective of currently living households before the realization of the severity of climate damage or the idiosyncratic income process.

6 Analysis

Implementing a carbon tax with a uniform rebate yields a much higher optimal tax than in the representative agent case. In Figure 1 we plot the welfare gain (in consumption equivalent) over a range of the carbon instrument. The utilitarian optimum tax under incomplete markets is \$571/tC, while the representative agent optimum is only \$67/tC.

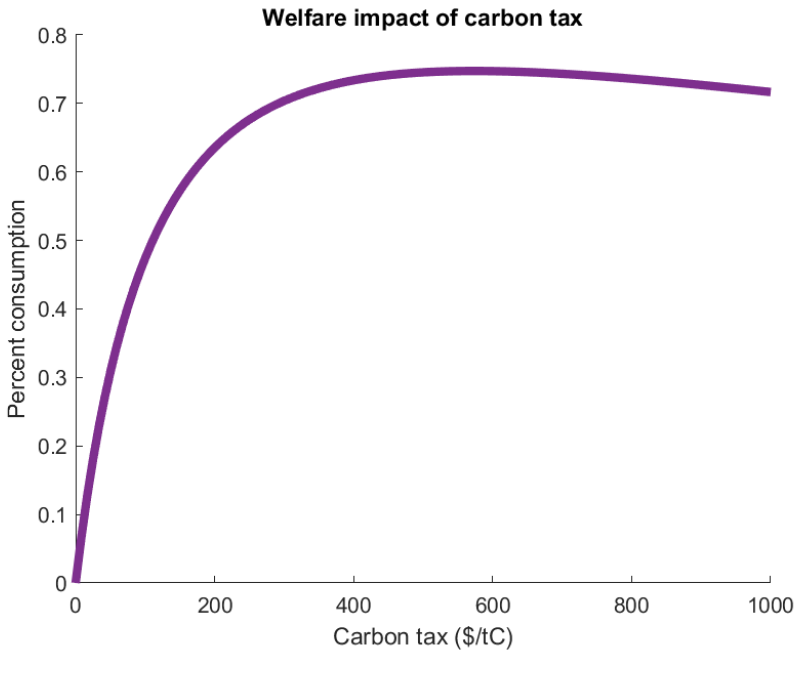

Figure 1: Utilitarian welfare response to carbon tax. This is the total welfare response, measured in consumption equivalent, to different values of the carbon tax.

In both frameworks the regulator wants to impose a carbon tax in order to internalize the climate externality and increase the availability of total resources. Since climate change damages output, a positive carbon price reduces the amount of economic losses related to the atmospheric stock of carbon, which results in a welfare gain. Eventually the tax on carbon becomes too high and the distortions to the firm's production decisions too great, causing aggregate resources to fall. However, in the incomplete markets model there are two additional channels through which the carbon tax affects welfare, redistribution and public insurance.

In regards to the redistribution motive, since we have a distribution of households with very different levels of consumption, there are welfare gains that stem from taxing energy use and distributing the revenue equally to each household. This comes from the fact that an extra unit of consumption for the poor has a much higher marginal utility than for the rich, while the carbon tax affects income proportionally through a change in aggregate prices.

When insurance markets are incomplete, and households face idiosyncratic income risk, the carbon policy increases welfare through an insurance motive. Specifically, risk averse households stand to benefit from a reduction in exposure to the risk from both climate change and income shocks, when potential climate damage is reduced and the carbon tax rebate provides a source of income independent of labour risk. While the regulator in the representative agent framework also faces climate risk, the insurance channel becomes much stronger when markets are incomplete.

With inequality, these various channels matter differently for different households, depending on their position in the distribution. First, from a re-distribution perspective, clearly the uniform rebate matters more for poor households than those higher up the distribution. The more uneven that income and wealth are distributed, the more the poor have to gain form the re-distributive properties of the carbon policy. This implies a preference for a higher carbon tax from poor households.

Second, the existence of credit constraints - a reality for a large portion of the global poor - makes risk much more costly. Households would like to have stable consumption, but may not be able to accomplish smoothing without proper access to credit markets. Those who do have access to credit markets still suffer from income risk. Ideally, they would like to borrow and save different amounts depending on the future state of the economy and their own income state, but such instruments do not exist. In response, households will self insure by accumulating precautionary savings, who, as risk rises, incur greater and greater welfare loss. Clearly, the poor are most hurt by idiosyncratic and climate risk, as they are subject to both of these market failures, and not able to borrow or smooth their consumption across future states of the world. The carbon policy, through decreasing the volatility of income, works to reduce the costs arising from market incompleteness.

Figure 2 shows the most-preferred level of the carbon tax of each agent. This is the policy that a household with a given level of cash on hand (their total period 1 endowment) in the initial period would choose to prevail globally in the future. Individual welfare impacts are conditional on agent characteristics included in the model, i.e. wealth, k, and labour productivity, h. $\lambda_i(k,h)$ 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.

$$\sum_{t=1}^{2} \beta^{t-1} \mathbf{E}[u((1+\lambda_i(k,h))c^*_{i,t})] = \sum_{t=1}^{2} \beta^{t-1} \mathbf{E}[u(\tilde{c}_{i,t})] \tag{15}$$

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

There is a wide range of preferences for carbon policy, with the richest households preferring $\$59/tC$, a similar level to the optimal tax under the representative agent framework. Poor households want a significantly higher level of the carbon policy, with those at or near the constraint preferring $\$672/tC$. Both the re-distribution and insurance channel create dispersion in policy preference along the distribution.

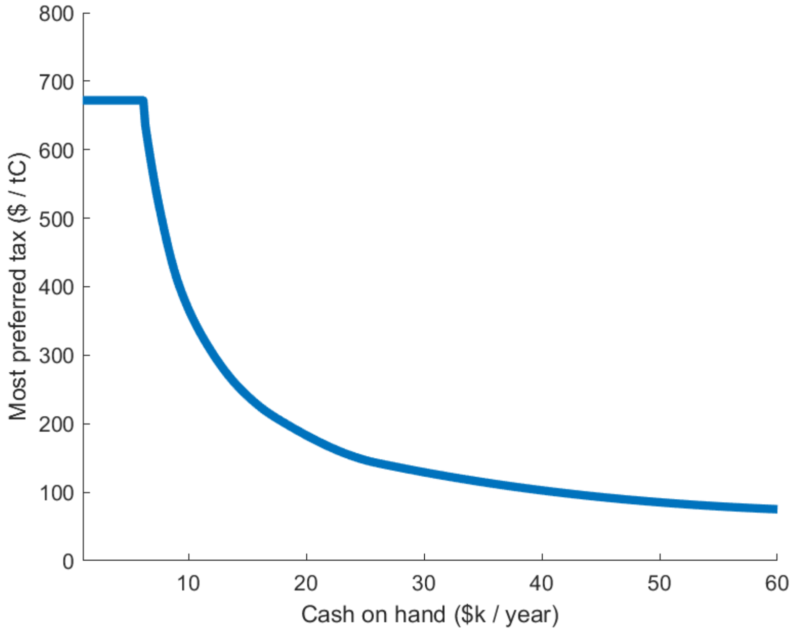

Figure 2: Most preferred carbon tax by household cash position. This figure shows the relationship between a household's position in the distribution and the level of the carbon tax which maximizes their individual welfare (their bliss policy). The kink occurs at the level of cash on hand where households are no longer bound by the credit constraint. Richer households prefer lower carbon taxes.

All constrained households have the same tax preference independent of the level of their cash on hand, because, in expectation, they have the same future income. This is reflected in the horizontal section of the curve in Figure 2. Rich households transfer substantial adaptation resources to the future in order to smooth consumption and address climate and income risk. Thus the carbon tax rebate is much less important for them. Meanwhile poor households face much steeper costs to transfer adaptation resources.

It is worth noting that in a more rich setting, taxing carbon could also have counter-acting regressive tendencies to the channels that we explore in the current framework. Poorer households often consume more carbon-intensive consumption bundles, and thus an increase in the price of those goods would disproportionately affect their welfare. However, the existence of multiple goods would not extinguish the risk channel (nor the redistribution) that we explore here.

How do these household level responses translate into deciding on a single optimal value for the carbon policy? The aggregate welfare change under the utilitarian welfare function can be decomposed into the three channels discussed above. We follow the decomposition method detailed in Floden (2001), where total welfare change is separated into: the gains from increasing the *level* of consumption, ω_{lev}, since climate change causes damage to aggregate production; the gains from decreasing *uncertainty*, ω_{unc}, since households are risk averse; and the gains from decreasing *inequality*, ω_{ine}, since utility is concave. The contribution of these three channels approximately sum to ω_U, the total utilitarian welfare gain described above.[16] Since the carbon tax and rebate can affect all three of these channels, it is interesting to know how much each channel matters, quantitatively, when choosing the optimal utilitarian tax level. In addition, if one believes that the gains from reducing inequality due to the re-distributive nature of the policy should not be considered, it is possible to choose an optimal tax measure that omits this component.

The decomposition approach is as follows. First define certainty equivalent consumption bundle, $\bar{c}_i$, for household, i, as the level of consumption that satisfies: $u(\bar{c}_i) = \mathbf{E}[u(c_i)]$. In addition, define average consumption, $C = \sum_i c_i/n$, and average certainty equivalent, $\bar{C} = \sum_i \bar{c}_i/n$. The aggregate gain (loss) in welfare resulting from increased (decreased) consumption level is:

$$\omega_{lev} = \frac{\mathbf{E}C^B}{\mathbf{E}C^A} - 1 \tag{16}$$

where C^B is average consumption under a carbon tax policy, and C^A is average consumption under business-as-usual.

Let p_{ine}, be the cost of inequality, which satisfies:

$$u((1 - p_{ine})\bar{C}) = \sum_i \mathbf{E}[u(\bar{c}_i)/n] \tag{17}$$

This is the difference between the utility of consuming the average certainty-equivalent and the average of certainty-equivalent utilities. Thus risk has been scrubbed from consideration.

Let p_{unc} be the cost of uncertainty, which satisfies:

$$\mathbf{E}u((1 - p_{unc})C) = u(\bar{C}) \tag{18}$$

This is the difference between expected average consumption and the average certainty-equivalent. Thus inequality has been scrubbed from the measurement.

With these costs, we can identify the welfare gain from their respective channels. The welfare gain from reducing inequality, ω_{ine} is given by:

[16] Floden (2001) proves this relationship for the standard incomplete markets setting without aggregate risk. In our setting with aggregate climate risk, this approximate relationship also holds over the relevant policy range.

$$\omega_{ine} = \frac{1 - p^B_{ine}}{1 - p^A_{ine}} - 1 \tag{19}$$

And the welfare gain from reducing risk, ω_{unc} is given by:

$$\omega_{unc} = \frac{1 - p^B_{unc}}{1 - p^A_{unc}} - 1 \tag{20}$$

The welfare gained from these three channels approximately combine to the total welfare gain, ω_U, under the following relationship:

$$\omega_U = (1 + \omega_{lev})(1 + \omega_{ine})(1 + \omega_{unc}) - 1 \tag{21}$$

The results from the baseline experiment are presented in Figure 3 below. The utilitarian optimal value of this carbon policy is $\$571/tC$, when the benefits from all three welfare channels are take into consideration. If re-distributive gains are not included, the value falls to $\$260/tC$.

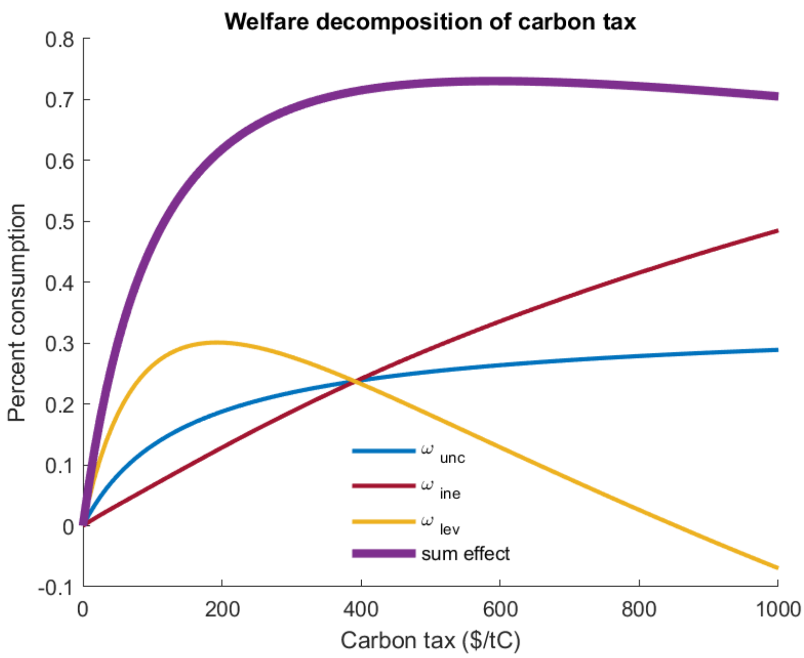

Figure 3: Decomposition of aggregate welfare response. This figure illustrates the decomposition of the utilitarian welfare response into its three components: the effect on the level of consumption, ω_{lev}, the re-distribution effect, ω_{ine}, and the risk channel, ω_{unc}. These three components approximate sum to the aggregate welfare response illustrated in Figure 1

Over the range of these taxes, the benefits of reducing inequality and uncertainty are of similar value. However, as the carbon tax level grows the distortion on output begins to outweigh the benefits of addressing the climate externality. In the incomplete markets setting, there continues to be value to using distortionary taxation to raise revenue and rebate it, however the gains from reducing uncertainty diminish and the gains from reducing inequality, while still strong, are not enough to justify higher levels of the carbon tax. This decomposition analysis shows that there are considerable co-benefits to implementing a basic uniform rebate of the carbon tax revenue - even in the absence of re-distributive motives.

Other welfare measures

The utilitarian welfare function is only one possible metric for choosing the carbon tax level. For example, a median voter approach finds a higher tax, $\$672/tC$, given the degree of inequality we observe and the preference for high carbon taxation among the poorer households. Alternatively, if we constrain the utilitarian tax choice to be *Pareto optimal*, such that no household is made worse off under the policy, we find a value of $\$143/tC$. Essentially, due to the monotonicity of policy preference in cash on hand detailed in Figure 2, this is equivalent finding the highest carbon tax level that makes the wealthiest household indifferent between the policy and the unregulated equilibrium. From a political economy perspective, this would be a policy that is palatable for every household, and still significantly higher than under the representative agent framework.

Comparison to other frameworks

It is worthwhile to place our quantitative results with some estimates from other comparable frameworks. However, we want to make a few cautionary notes for these comparisons. First, it should be obvious that our prices are derived with a different experiment to ones that allow coordinated global action immediately. Second, beyond the wide range of assumptions made about damages, preferences, and discounting, we have opted for a simple production-side model, and a relatively simple carbon cycle. Thus we emphasize the qualitative conclusions that can be drawn by comparing carbon pricing *within* our framework. Namely the analysis of incomplete markets, inequality and borrowing constraints relative to the absence of these frictions.

The social cost of carbon estimated in Golosov et al. (2014) gives a value of $\$56.9/tC$ for the ex ante optimal tax. This is higher than the optimal tax derived by DICE in Nordhaus (2008), which is computed to be $\$34/tC$ in 2010, rising to $\$90/tC$ in 2050. In terms of magnitude it is clear that these values are much more in line with the representative agent case in our analysis. There are studies that derive suggested carbon prices that have magnitudes which are more in line with the utilitarian optimal tax derived in our incomplete markets framework. For example, by assuming a much lower inter-temporal discount rate, Stern (2007) derives a high optimal tax value, reaching approximately $\$600/tC$ in 2050; and Dennig et al. (2015) find high values when climate damages explicitly fall disproportionately on low income consumers with a range between $\$400 - 1000/tC$ in 2050, depending on the chosen income elasticity of damage.

We believe our work is complementary to the work done on including explicitly regressive impacts of climate change, as it shows the regressive cost of risk. In addition, the co-benefits associated with the public insurance channel are an alternative argument for stronger climate action which does not require (implausibly) low discount rates.

6.1 Correlated climate and income risk

There is empirical evidence that suggests climate damage is not proportional to income, and that in fact, low income households are explicitly more exposed to climate change-related losses. In this section we explore the case where climate and income risk are positively correlated. Specifically, we assume that in the bad aggregate climate state income inequality rises, such that the global income inequality reaches 0.64 Gini. This is achieved through applying a mean-preserving spread on labour productivity, that yields both expected losses and extreme losses that are in line with certainty-equivalent projections in Krusell and Smith Jr (2015). In the good climate state, income inequality remains as it is in our base experiment above. We maintain the assumption of equalized idiosyncratic risk profiles (income transition probabilities are i.i.d), this has the effect of increasing the amount of risk for all agents, while maintaining the level of expected earnings for a given aggregate wage.

Figure 4 illustrates the change in the individual response to the carbon policy when including correlated climate and income risk. 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 applies to the risk premium in our scenario. All households are now exposed to the possibility of increased adverse income shocks when climate change losses are catastrophic, raising the value of insurance. This increases the precautionary motive across all households, and thus increases the value of the carbon tax for all households. However, it is clear that those who stand to gain the most from coordinated action are the constrained households, who are the most exposed to the additional risk.

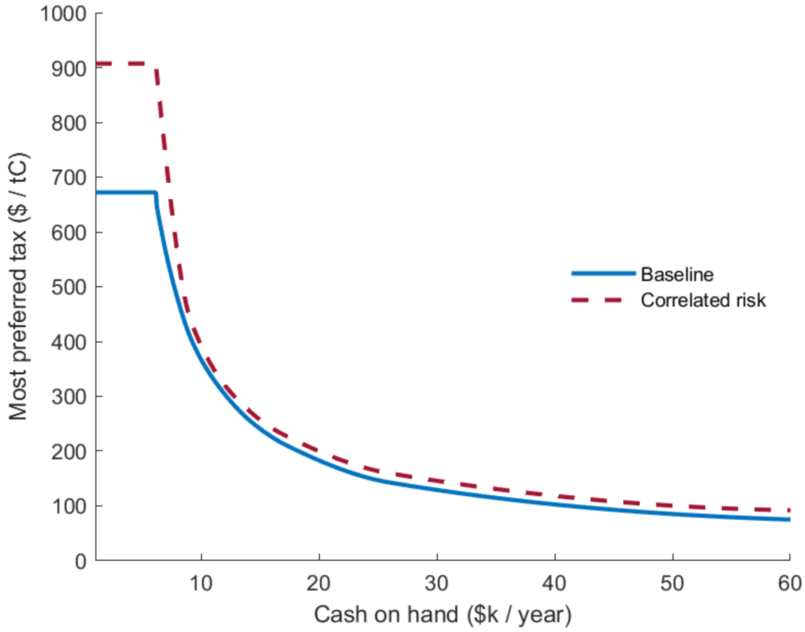

Figure 4: Most preferred carbon tax by household position - correlated risk experiment. This figure shows the change in tax preference when income risk becomes correlated with climate risk. The shift between scenarios illustrates the cost that risk imposes across the distribution, where expected losses are held constant, but the dispersion increases such that climate change-related losses are concentrated in the lower tail.

What does this mean for the optimal tax? When all welfare channels are taken into account, the utilitarian regulator chooses $\$739/tC$ or, if the gains from redistribution are omitted, $\$319/tC$. Thus the addition of correlated risk translates into an increase in the optimal tax primarily driven by the vulnerability of constrained households. A comparison of these two scenarios is summarized in Table 2.

Scenario	Utilitarian	No redist.	Pareto	Range
Baseline	571	260	143	[59 - 672]
Correlated risk	739	319	227	[84 - 907]

A collection of optimal tax concepts across the two scenarios. All taxes are in $\$/tC$. The *Utilitarian* optimal tax includes all three welfare channels, while the *No redist.* tax is the optimal tax when the gains from redistribution are omitted from consideration. The *Pareto* optimal tax requires that no agent is made worse off under the policy. The Range of the distribution of most-preferred carbon tax values are included in the final column.

Table 2: Optimal tax concepts

7 Conclusion

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.

We have examined the individual response to carbon taxation along a realistic global distribution of households. Using a welfare decomposition method we have also quantified the three channels through which a utilitarian regulator chooses the optimal tax. When including all three channels, the utilitarian regulator would set the tax an order of magnitude larger than under the representative framework. Both the re-distribution and risk channels create substantial welfare gains. Even if re-distributive motives are ignored, the optimal tax is four times larger than under the complete markets assumption, indicating that there are significant insurance co-benefits associated with carbon taxation. In addition, we have shown that the case where climate and idiosyncratic risk are correlated, a more empirically plausible case, the insurance channel becomes even stronger and thus the optimal tax rises by all measures.

We see this work as complementary to the important work being done on inequality and climate change. Admittedly, there are other significant dimensions of heterogeneity that remain unexplored by our framework. In our analysis we have put the emphasis on vertical inequality and the cost of risk, highlighting the potential for carbon taxation to fulfil the role of public insurance - creating large welfare co-benefits of stronger action on climate change. Combined with considerations of geographic heterogeneity and other horizontal inequities, this result can inform further work on the complicated calculus of climate policy. In particular, we see a great potential for this welfare analysis to be combined with concerns over the regressive impacts of carbon taxation.

8 Appendix

8.1 Carbon cycle

The framework abstracts from temperature and 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.

$$1 - d(s) = \varphi_L + (1 - \varphi_L)\varphi_0(1 - \varphi)^s \tag{22}$$

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, $S_{depr,t} = \varphi S_{depr,t-1} + \varphi_0(1 - \varphi_L)E_t$.

For the stylized model experiment period, a marginal emissions impulse will retain, $0.2 + (1 - 0.2)0.4(1 - 0.109)^1 = 0.49$ of its carbon in the atmosphere.

8.2 Alternate damage elasticity

This section includes optimal tax calculations for a calibration with lower climate damage elasticity, equal to those specified in Golosov et al. (2014). In expectation, the damages reflect an aggregate loss of roughly 2.5%. Other than θ_{high} and θ_{low}, all other calibration objects are held constant to the baseline model calibration detailed in Table 1. Table 3 summarizes these results.

Scenario	Utilitarian	No redist.	Pareto	Range
No correlated risk	520	210	0	[0 - 622]
Correlated risk	689	269	76	[34 - 840]

A collection of optimal tax concepts across the two idiosyncratic risk assumptions for a lower climate damage elasticity assumption. In expectation and without intervention, aggregate climate losses are equal to about 2.5% in 2100. All taxes are in $\$/tC$. The *Utilitarian* optimal tax includes all three welfare channels, while the *No redist.* tax is the optimal tax when the gains from redistribution are omitted from consideration. The *Pareto* optimal tax requires that no agent is made worse off under the policy. The *Range* of the distribution of most-preferred carbon tax values are included in the final column.

Table 3: Optimal tax concepts for alternate climate damage specification

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