Fiscal Policy for Climate Change

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Fiscal policy offers a number of levers to reduce carbon emissions. Climate change mitigation can for example be implemented through carbon taxation on the production or consumption side, or through debt-financed public investments in emission-reducing infrastructure. Yet these various instruments may differ significantly in their cost-effectiveness in reducing emissions and in their distributional impacts among households. We develop a macroeconomic heterogeneous-agent model with environmental externalities to address both of these questions. In this model, households derive utility from the consumption of carbon-intensive and clean goods, and from the environmental damages resulting from CO_2 emissions. In addition, CO_2 emissions affect productivity and thus relative prices. We use household data on the distribution carbon-intensive goods consumption to estimate preference parameters. Starting from a realistic fiscal structure, we then implement various tax reforms to analyze their effects on both CO_2 emissions and welfare along the income distribution.

JEL: E62, H23, Q54, Q58

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I. Introduction

Anthropogenic climate change has become one of the leading issues facing policymakers globally. Implementing a uniform Pigouvian tax on greenhouse gas emissions – mainly carbon dioxyde – is considered by most economists to represent the first best to address climate change (Nordhaus, 2019). Yet, enacting carbon pricing at a level commensurate with countries' emissions reduction commitments has so far proven politically difficult (Hassler, Krusell and Olovsson, 2021). In particular, in the absence of redistribution carbon taxation is usually regressive in advanced economies (Stavins, 2020). This impacts the perceived fairness and acceptability of a consumption-side carbon tax negatively (Douenne and Fabre, forth.).

This state of affairs heightens the need to examine the macroeconomic and distributional impacts of alternate climate change mitigation policies. Fiscal policy in particular offers a number of levers to tackle greenhouse gas emissions besides use-side carbon pricing. Policymakers can for example implement carbon taxation on the production side, or use public debt to finance infrastructure investments to decarbonize the most fossil-fuel intensive sectors, such as transportation and electricity production (IPCC, 2018).

In the present paper, we develop a macroeconomic heterogeneous-agent model with environmental externalities to assess the macroeconomic and distributional impacts of these alternative fiscal policy tools in mitigating climate change. We consider an economy consisting of a carbon-intensive and a clean sector, which produce a carbon-intensive and carbon-free goods respectively. A continuum of households derive utility from the consumption of these two goods and from climate-related damages resulting from greenhouse gas emissions. Importantly, the model includes a rich and realistic set of fiscal tools that can be used to set a price on the carbon externality, including consumption-side, production-side and capital taxes, and lump-sum transfers.

Our contribution relates to various recent strands of the climate macroeconomics literature. Our model builds on seminal evaluations of the optimal price of carbon such as Nordhaus (2014, 2018) and Golosov et al. (2014*a*). In particular, we include a climate damage function directly inspired by Golosov et al. (2014*a*). Yet this paper is even more closely related to the burgeoning literature that departs from the representative agent assumption in climate macroeconomics. In particular, we adapt the heterogeneous-agent framework in a climate change setting, in the vein of Fried (2021) and Känzig (2022). By contrast with these recent contributions, we seek to represent the full joint distribution of households' income and the carbon intensity of their final consumption. Our paper is also related to Barrage, who explores the impact of carbon taxation when governments also levy distortionary taxes, particularly on capital income. However this assessment is conducted in a representative agent framework and abstracts from distributional considerations.

We build a full-fledged heterogeneous-agent model, which reproduces both income and wealth inequality and the heterogeneity in the consumption of carbon-intensive (brown) goods in total consumption. To account for the observed heterogeneity in this new dimension, we then estimate the parameters of the utility function using the Simulated Method of Moment to match the empirical distribution (by decile) of brown goods. This is necessary to yield a quantitatively relevant welfare effect of any policy to reduce carbon emission.

To calibrate this distribution, we build a detailed estimate of households direct emissions in the United States by income decile. We combine household-level fossil-intensive energy expenditure obtained from the Consumer Expenditure Survey with state-level prices and carbon intensity factors for each energy vector.

In the current version of this paper, we perform policy experiments to assess the change in equilibrium inequality and carbon emissions for various simple policies. In future revisions, we will apply advanced modelling tools to derive optimal policies in heterogeneous agent models, building on LeGrand and Ragot (2021). This 'truncation method' to solve heterogeneous agents models allows us to derive the optimal time-varying path and allocation of taxes and public debt to reduce carbon emission, while minimizing the welfare cost of the transition and accounting for inequality dynamics.

The paper is laid out as follows. Section II presents the model and details its specification. Section III describes the calibration of the households' consumption share of the carbon intensive good, model parameters, the baseline fit of our model to the calibration data. Section IV presents comparative statics results when modeling counterfactual scenarios on the price of the clean and carbon-intensive goods.

II. A heterogeneous-agent model with environmental externalities

We consider a discrete time-economy populated a continuum of agents with unit mass. Agents are distributed on an interval $\mathcal{I}$ according to measure ℓ. The law of large numbers is assumed to hold (see Green, 1994).

A. Production

The economy features two final consumption goods, that differ according to their pollution intensity. For the sake of simplicity, these two consumption goods will be called Green and Brown and indexed by $s = G, B$. The two goods are produced in two different sectors by a representative firm. These representative firms transform capital and labor into final goods.

Capital sector

Capital is fungible and common to both sectors. Investments in both sectors are aggregated together into capital by a unique representative firm. These investments, denoted by $I_{G,t}$ and $I_{B,t}$ are used to produce aggregate investment I_t according to the following CES production function:

$$I_t := \left(\omega_{G,K} I_{G,t}^{\alpha_K} + \omega_{B,K} I_{B,t}^{\alpha_K}\right)^{\frac{1}{\alpha_K}}, \tag{1}$$

where $(1-\alpha_K)^{-1}$ is the elasticity of substitution between the two inputs, with $\alpha_K \in (0,1)$. Capital is used as the numeraire in the economy. We denote by $\tilde{p}_{G,t}$ and $\tilde{p}_{B,t}$ the prices of final consumption goods in terms of capital good. The firm producing capital chooses input quantities $I_{G,t}$ and $I_{B,t}$, so as to maximize its profit $I_t - \tilde{p}_{G,t} I_{G,t} - \tilde{p}_{B,t} I_{B,t}$, which implies:

$$I_{G,t} = \left(\frac{\tilde{p}_{G,t}}{\omega_{G,K}}\right)^{\frac{1}{\alpha_K - 1}} I_t \text{ and } I_{B,t} = \left(\frac{\tilde{p}_{B,t}}{\omega_{B,K}}\right)^{\frac{1}{\alpha_K - 1}} I_t. \tag{2}$$

Using the FOCs (2) with the no-profit condition of the capital-firm, we obtain the following relationship between prices:

$$1 = \left(\omega_{G,K}^{\frac{1}{1-\alpha_K}} \tilde{p}_{G,t}^{\frac{\alpha_K}{\alpha_K - 1}} + \omega_{B,K}^{\frac{1}{1-\alpha_K}} \tilde{p}_{B,t}^{\frac{\alpha_K}{\alpha_K - 1}}\right)^{\frac{\alpha_K - 1}{\alpha_K}}. \tag{3}$$

Goods sectors

We now turn to the production of the two final consumption goods. Each of these goods is produced by a representative firm endowed with a Cobb-Douglas production function featuring constant returns to scale. Productivity A_s, capital share α_s and depreciation rate δ_s are specific to each sector $s = B, G$. Capital is rent at the pre-tax rate, while pre-tax labor wage is allowed to be sector-specific and denoted by $\tilde{w}_{s,t}$. If K_s and L_s represent the capital and labor supplies, the firm's objective in sector s, expressed in capital prices, can be written as follows:

$$\max_{(K_{s,t}, L_{s,t})_{t \geq 0}} F_s(K_{s,t-1}, L_{s,t}) - \tilde{w}_{s,t} L_{s,t} - \tilde{r}_t K_{s,t-1}, \tag{4}$$
$$\text{where } F_s(K_{s,t-1}, L_{s,t}) := \tilde{p}_{s,t} A_{s,t} K_{s,t-1}^{\alpha_s} L_{s,t}^{1-\alpha_s} - \delta_s K_{s,t-1},$$

is the sector s production function. Note that the firm's production function (4) requires capital to be installed one period ahead. The firm's profit maximization then implies the following factor prices:

$$\tilde{r}_t = \alpha_s \tilde{p}_{s,t} A_{s,t} K_{s,t-1}^{\alpha_s - 1} L_{s,t}^{1-\alpha_s} - \delta \text{ and } \tilde{w}_{s,t} = (1-\alpha_s)\tilde{p}_{s,t} A_{s,t} K_{s,t-1}^{\alpha_s} L_{s,t}^{-\alpha_s}. \tag{5}$$

where $\tilde{p}_{G,t}$ and $\tilde{p}_{B,t}$ are the price of green and brown good in terms of green goods respectively. We assume that labor and capital are fully mobile across sectors. Total labor supply is assumed to be fixed.

Pollution

We assume that the brown good produces CO_2 emissions as a negative externality. The emission intensity per unit of brown good is assumed to be constant and equal to m. So, if $Y_{B,t-1}$ is the brown good production in period $t-1$, the associated CO_2 emissions in period t amounts to $mY_{B,t-1}$. We do not consider the potential introduction of a technology enabling to draw down accumulated CO_2 in the atmosphere (such as *e.g.* a direct air capture technology), but the emission stock is assumed to deplete at a constant rate of $d_m \geq 0$. The emission stock in period t, M_t, verifies the following recursion:

$$S_t = mY_{B,t-1} + S_{t-1}(1-d_m). \tag{6}$$

As is common in the literature, we assume that CO_2 emissions impact production through a damage function which affects sector productivity. Considering the damage function $D_s(S_t)$ on sector s as a function of emissions S_t, we assume that the productivity of sector s can be written as follows:

$$A_{s,t} := A_{0,s} A_t (1 - D_s(S_t)). \tag{7}$$

Excluding damages, productivity growth is the same in both sectors; this shared productivity is denoted by A_t. Productivity levels in each sector are adjusted by scaling parameters $A_{0,s}$. For the specification of the damage function, we follow

Golosov et al. (2014*b*) and assume the following functional form:

$$D_s(S_t) := 1 - e^{-\gamma_s(S_t - \overline{S})}, \tag{8}$$

where $\gamma_s > 0$ is a sector-specific scaling parameter and $\overline{S} > 0$ represents the pre-industrial atmospheric CO_2 concentration. The model therefore verifies $S_t \geq \overline{S}$. The functional form (8) is a highly stylized yet acceptable approximation of simple climate models in the context of our model.

B. Government

We consider a benevolent government that can influence CO_2 atmospheric emissions through a rich taxation scheme. For the sake of simplicity, we rule out the presence of exogenous public spending, even though the government can choose negative taxes, and hence to subsidize one sector of the economy. We consider taxes on consumption, labor, capital, as well as a lump-sum transfer.

Consumption taxes $\tau^c_{s,t}$ are assumed to be sector-specific. If $C_{s,t}$ is the aggregate consumption in sector s, then government derives an income revenue from consumption tax $\tau_{s,t}$ equal to $\tilde{p}_{s,t}\tau^c_{s,t}C_{s,t}$. We denote by $p_{s,t}$ the post-tax price of good s, which is defined as:

$$p_{s,t} = (1 + \tau^c_{s,t})\tilde{p}_{s,t}. \tag{9}$$

The labor tax $\tau^w_{s,t}$ is also assumed to be sector specific. However, since we assume complete labor mobility between green and brown sectors, we have an identical post-tax wage w_t in both sectors. Formally:

$$w_t = (1 - \tau^w_{B,t})\tilde{w}_{B,t} = (1 - \tau^w_{G,t})\tilde{w}_{G,t}. \tag{10}$$

Capital tax τ_t on financial returns is identical in both sectors and the post-tax rate r_t is defined as:

$$r_t = (1 - \tau_t^K)\tilde{r}_t.$$

Denoting by T_t the date-t lump-sum transfer to agents, the governmental budget constraint can then be written using the previous elements as follows:

$$\begin{aligned}(11) \qquad T_t \leq \tau_t^K \tilde{r}_t(K_{B,t-1} + K_{G,t-1}) + (\tau_{B,t}^w L_{B,t} + \tau_{G,t}^w L_{G,t})\tilde{w}_t \\ + \tilde{p}_{G,t}\tau_{G,t}^c C_{G,t} + \tilde{p}_{B,t}\tau_{B,t}^c C_{B,t}.\end{aligned}$$

Taking advantage of the fact that production functions are homogeneous of degree one, the governmental budget constraint can also be written as:

$$\begin{aligned}(12) \quad T_t + r_t(K_{B,t-1} + K_{G,t-1}) + w_t(L_{B,t} + L_{G,t}) \leq \tilde{p}_{G,t}\tau_{G,t}^c C_{G,t} + \tilde{p}_{B,t}\tau_{B,t}^c C_{B,t} \\ + F_B(K_{B,t-1}, L_{B,t}) + F_B(K_{G,t-1}, L_{G,t}),\end{aligned}$$

where F_s is the production function in sector s.

C. Households

The economy is populated by a unit mass of households, who face an uninsurable income risk. The income process y takes n possible distinct values, denoted $y_1, \ldots, y_N$ and follows a first-order Markov chain with a constant transition matrix Π. We denote by s_k the share of agents endowed with income y_k – where $\sum_{k=1}^N s_k = 1$. The vector $\boldsymbol{s} = (s_1, \ldots, s_N)$ corresponds to the stationary probability associated to matrix Π: $\boldsymbol{s}\Pi = \boldsymbol{s}$.

We normalize the labor supply of each household to one, such that the aggregate labor supply $\overline{L}$ verifies:

$$\overline{L} = \sum_{k=1}^N s_k y_k.$$

Household types

Besides ex-post heterogeneity related to income risk realization, we assume that households differ according to a type θ that affects their preferences. The type of an agent is exogenous, fixed over time and picked from a finite set Θ. This preference heterogeneity may reflect heterogeneity in choice of residential location and taste for brown goods.

Preferences

Households have time-additive preferences and per period utility is discounted with a common discount factor $\beta \in (0,1)$. In each period, households derive utility from consumption of brown and green goods, denoted by c_B and c_G respectively. Brown and green goods are partial substitutes and aggregated through a CES aggregator, which is household type-specific. For a household of type θ, the share parameters are denoted by $\omega_{G,\theta}, \omega_{B,\theta} \in [0,1]$ (with $\omega_{G,\theta} + \omega_{B,\theta} = 1$), while the elasticity of substitution is equal to $(1-\alpha_\theta)^{-1}$, with $\alpha_\theta \in [0,1)$. The aggregation also features subsistence consumption levels $\bar{c}_{G,\theta} \geq 0$ and $\bar{c}_{B,\theta} \geq 0$. The aggregate consumption good $C_\theta(c_G, c_B)$ can then be formally expressed as:

$$C_\theta(c_G, c_B) = \left(\omega_{G,\theta}\left(c_G - \bar{c}_{G,\theta}\right)^{\alpha_\theta} + \omega_{B,\theta}\left(c_B - \bar{c}_{B,\theta}\right)^{\alpha_\theta}\right)^{\frac{1}{\alpha_\theta}}. \tag{13}$$

Instantaneous utility $U_\theta(c_G, c_B)$ is assumed to be defined over this aggregate good:

$$U_\theta(c_G, c_B) = u\left(C_\theta(c_G, c_B)\right),$$

where $u : \mathbb{R}_+ \to \mathbb{R}$ is strictly increasing, strictly concave and independent of agent's types. For the sake of simplicity, we assume that intertemporal elasticity of aggregate consumption is constant and equal to $\sigma^{-1} > 0$, such that $u(c) = \frac{c^{1-\sigma}-1}{1-\sigma}$.

Households' program

We consider a household of type θ, currently endowed with beginning-of-period wealth a and income y. They have to decide how much brown and green goods to consume and how much to save. We take advantage of the results of Açikgöz (2016) to express the households' program in recursive form. We denote by $V^\theta(a, y)$ the value function of the household of type θ, beginning-of-period wealth a, and income y. Formally, we have:

$$V^\theta(a, y) = \max_{(c_G, c_B, a')} u\left(C_\theta(c_G, c_B)\right) + \beta \mathbb{E}_{y'}\left[V^\theta\left(a', y'\right)\right], \tag{14}$$

$$\text{subject to } a' = (1 + r)a + wy + T - p_G c_G - p_B c_B, \tag{15}$$

$$a' \geq 0, \tag{16}$$

$$c_G, c_B > 0, \tag{17}$$

where $\mathbb{E}_{y'}$ is the expectation over future income realizations y'.

We denote by λ and μ the Lagrange multipliers on the budget constraint (15) and the credit constraint (16), respectively. Combining the first-order condition and the envelop conditions on a yields the following Euler equation on the Lagrange multiplier λ:

$$\lambda = \beta \mathbb{E}\left[(1 + r')\lambda'\right] + \kappa. \tag{18}$$

The first-order conditions on green and brown consumption choices imply:

$$\lambda = \frac{1}{p_G} \frac{\partial C_\theta(c_G, c_B)}{\partial c_G} u'\left(C_\theta(c_G, c_B)\right) = \frac{1}{p_B} \frac{\partial C_\theta(c_G, c_B)}{\partial c_B} u'\left(C_\theta(c_G, c_B)\right), \tag{19}$$

which, after some algebra, is equivalent to:

$$\lambda = \frac{\omega_{G,\theta}}{p_G} (c_G - \bar{c}_{G,\theta})^{\alpha_\theta - 1} C_\theta(c_G, c_B)^{1-\alpha_\theta-\sigma}, \tag{20}$$

$$c_B - \bar{c}_{B,\theta} = \left(\frac{p_B \omega_{G,\theta}}{p_G \omega_{B,\theta}}\right)^{\frac{1}{\alpha_\theta - 1}} (c_G - \bar{c}_{G,\theta}), \tag{21}$$

Given the number of possible combinations implied by the Euler equation (18) and equalities (20) and (21), it is simpler to use one intertemporal equation and two static ones. Our choice enables us to follow the dynamics of the Green good, from which we deduce the consumption of the Brown good.

Simplifying the household's program

We can further simplify the model dynamics by expressing it solely as a function of green good consumption c_G. The idea is to use equation (21) to substitute for the expression of c_B. First, the budget constraint (15) becomes:

$$a' = (1+r)a + wy + \hat{T} - \hat{p}_G c_G, \tag{22}$$

$$\text{where: } \hat{T} = T - p_B \left(\bar{c}_{B,\theta} - \left(\frac{p_B \omega_{G,\theta}}{p_G \omega_{B,\theta}}\right)^{\frac{1}{\alpha_\theta - 1}} \bar{c}_{G,\theta}\right), \tag{23}$$

$$\text{and } \hat{p}_G = \left(\frac{p_B \omega_{G,\theta}}{p_G \omega_{B,\theta}}\right)^{\frac{1}{\alpha_\theta - 1}} p_G, \tag{24}$$

Second, equation (20) characterizing λ becomes:

$$\lambda = \frac{1}{p_G}\omega_{G,\theta} \left(\omega_{G,\theta} + \omega_{B,\theta} \left(\frac{p_B \omega_{G,\theta}}{p_G \omega_{B,\theta}}\right)^{\frac{\alpha_\theta}{\alpha_\theta - 1}}\right)^{\frac{1-\alpha_\theta-\sigma}{\alpha_\theta}} (c_G - \bar{c}_{G,\theta})^{-\sigma},$$

which can be plugged into the Euler equation (18). In the absence of aggregate shocks, the quantity $\frac{1}{p_G}\omega_{G,\theta} \left(\omega_{G,\theta} + \omega_{B,\theta} \left(\frac{p_B \omega_{G,\theta}}{p_G \omega_{B,\theta}}\right)^{\frac{\alpha_\theta}{\alpha_\theta - 1}}\right)^{\frac{1-\alpha_\theta-\sigma}{\alpha_\theta}}$ remains constant over time: it will thus cancel out in the Euler equation. We deduce that for households who are not credit-constrained, we have:

$$(c_G - \bar{c}_{G,\theta})^{-\sigma} = \beta \mathbb{E}\left[(1+r')(c'_G - \bar{c}_{G,\theta})^{-\sigma}\right], \tag{25}$$

while for credit-constrained households, we have:

$$a' = 0. \tag{26}$$

Market clearing.

We denote by $\Lambda : [0, \infty) \times \{y_1, \ldots, y_N\}$ the distribution of agents over the state space, equal to the Cartesian product of the asset and incomes spaces.[1] The financial market clearing condition implies that aggregate savings should equal total capital. Formally:

$$K = K_B + K_G = \int a'(a, y)\Lambda(da, dy),$$

where $a'(a, y)$ is the end-of-period savings policy function solving the households' program (14)–(17).

Market clearing for green and brown consumption goods can be written as follows:

$$C_s = \int c_s(a, y)\Lambda(da, dy), \; s = B, G,$$

where $c_G(a, y)$ and $c_B(a, y)$ are policy functions for green and brown goods respectively.

Finally, the market clearing of goods implies:

$$C'_s + K'_s = K_s + F_s(K_s, L'_s), \; s = B, G.$$

[1] The existence of Λ is proved in Açikgöz (2016).

III. Model calibration

A. *Distribution of households greenhouse gas emissions*

To calibrate the distribution of household carbon emissions as a function of income, following Levinson and O'Brien (2019) and Sager (2019), we obtain data on both household expenditure on each good k, $c_{i,k}$, and their associated greenhouse gas emissions intensities e_k in $\mathrm{kgCO_{2,eq}}$ per dollar:

$$m_i = \sum_k c_{i,k} e_k \tag{27}$$

Households' consumption emits GHG through two channels: either through the direct combustion of fossil fuels for energy-related use (*direct* emissions) or through the emissions embedded in the production of the goods and services they purchase (*indirect* emissions).

In the following, we focus on carbon taxation targeting households' direct emissions stemming from their consumption of petroleum-derived fuels (gasoline and diesel in particular), natural gas, electricity and coal. These are the most easily targeted through carbon pricing, as the carbon intensity of these energy goods can be more readily measured. Future revisions of the present paper will extend the estimation of households' carbon footprint to indirect emissions.

We estimate the distribution of direct household emissions in the United States in 2019. We obtain data on household's energy-related expenditure from the Consumer Expenditure Survey for the three fossil fuels aforementioned and electricity. To construct emission factors in monetary terms, we combine physical emission intensities expressed in $\mathrm{kgCO_{2,eq}}$ per energy unit (MMBtu or kWh) with energy price data.

The emission intensity of each fossil fuel, while slightly varying by grade in the case of petroleum-derived fuels, can be considered homogeneous across the US. We therefore obtain standard emission factors from the US Environmental Protection

Agency. However, the carbon intensity of electricity is a direct function of the local power mix, which is highly heterogeneous across state boundaries in the US. To correctly account for this variance, we obtain data on state-level average carbon intensity per kWh of electricity supplied from the US Department of Energy.

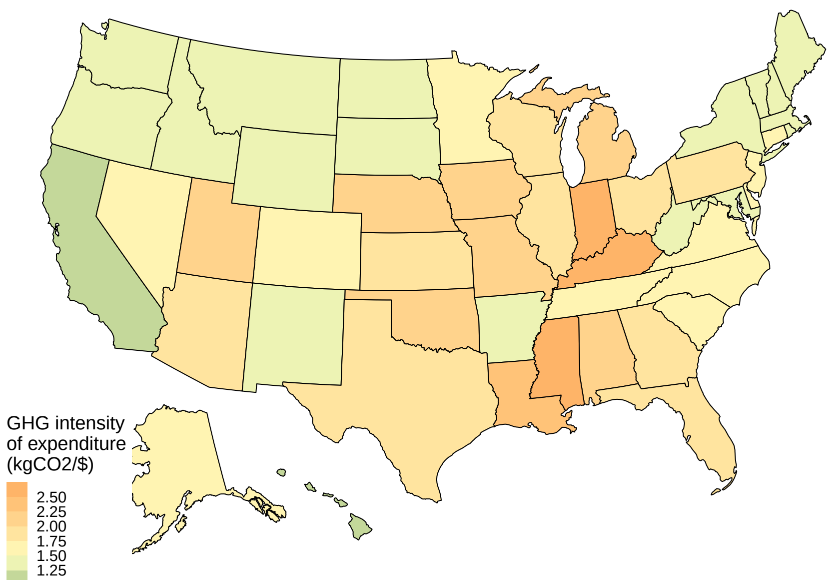

Figure 1. Direct emissions intensity of energy expenditure by state

We finally complement these physical emission factors with state-level energy prices for the five main vectors accounted for in our expenditure dataset: electricity, gasoline, diesel, natural gas and coal. We obtain price information in dollars per MMBtu from the US DoE State Energy Data System. The use of state-level data allows us to further account for the high underlying spatial variance in energy pricing: as an example, average electricity prices in 2019 in the continental US ranged from \$0.07/kWh in Louisiana to \$0.18/kWh in Rhode Island. The combination of physical emission intensities and energy price data allows us to compute the whole set of e_k at the state level. Figure 1 illustrates the spatial heterogeneity in emission intensity that our approach allows to recover.

This methodology allows us to compute emission intensity at the household level. Using CEX sampling weights, we construct an environmental Engels curve for direct GHG emissions by recovering emission intensities by total expenditure decile.

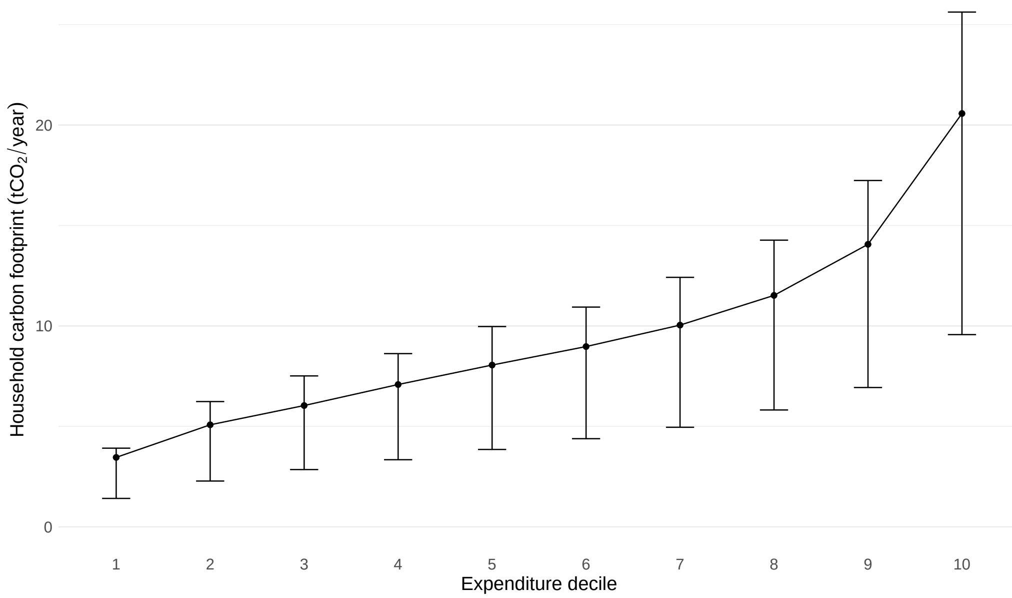

FIGURE 2. U.S. HOUSEHOLD DIRECT EMISSIONS BY DECILE OF EXPENDITURE

B. Model parameters

The main feature of this heterogeneous agent model is its capacity to generate a realistic level of income inequality and, most importantly, to replicate the consumption share of green and brown goods in the income distribution. This last property is key to match households' exposure to any change in the price of carbon in the economy. Our empirical strategy is thus to estimate the utility function of households to reproduce the share of consumption of green and brown goods in the economy.

Using the data of Figure 2, we first compute the share of brown goods in

Parameter	Description	Value
r	Interest rate	0.04
w	Wage	1.0
σ	Utility Function Curvature	2.0
$\bar{c}$	Brown Minimal Consumption	0.081
ρ	Income Shock Persistence	0.97
ϵ	Income Shock Std. Dev.	0.038
$\omega_{G,\theta}$	Green Consumption Utility Weight	0.994
$\omega_{B,\theta}$	Brown Consumption Utility Weight	0.006
α_θ	CES Substitution Parameter	-0.125
p_G	Post-tax Price of Green Good	1.0
p_B	Post-tax Price of Brown Good	1.0
τ_G^c	Tax on Green Consumption	0.0
τ_B^c	Tax on Browbn Consumption	0.0
T	Government Transfer	0.0

Table 1—the table

the total expenditure of households, ranked by expenditure decile. The data is reported in Figure 3, in red dots, on the left hand side. This graph shows that the consumption share of brown goods in the first expenditure decile is roughly 12% and goes down monotonically along the income distribution to fall to 6% in the last decile. This known property (see Känzig (2022) among others) implies that, although the absolute level of expenditure on brown goods increases with total expenditure, its share of total expenditure falls along the income distribution.

To replicate this distribution of brown goods consumption in the model, we implement a Simulated Method of Moments to reproduce 11 moments: the ten share of expenditure on brown goods by decile and the total share of aggregate consumption of green goods.

We first calibrate the standard parameters of the model. As a benchmark, we first normalize post-tax prices of each goods to 1 (which equivalently provides a normalization of the utility function). Second, the discount factor is set to $\beta = 0.96$ to match annual data. The real interest rate is set to $r = 4\%$, which is the standard value to match a realistic level of saving over total income. The real wage is set to 1 as a normalization of income. The overall utility curvature is to $\sigma = 2$, and the intertemporal elasticity of substitution to 0.5, which is a realistic value used in the literature. We will perform sensitivity test for these calibrated parameters in future revisions of the present paper. Following Castaeneda, Diaz-Gimenez and Rios-Rull (2003), the persistence of the uninsurable idiosyncratic income process ρ and the standard deviation of the income process ϵ are set to match realistic equilibrium inequality in wealth. At this stage, we target a Gini coefficient of wealth of roughly 0.7. We find $\rho = 0.97$. and $\epsilon = 0.038$, which are values which are consistent with empirical estimate of Krueger, Mittman and Perri (2018).

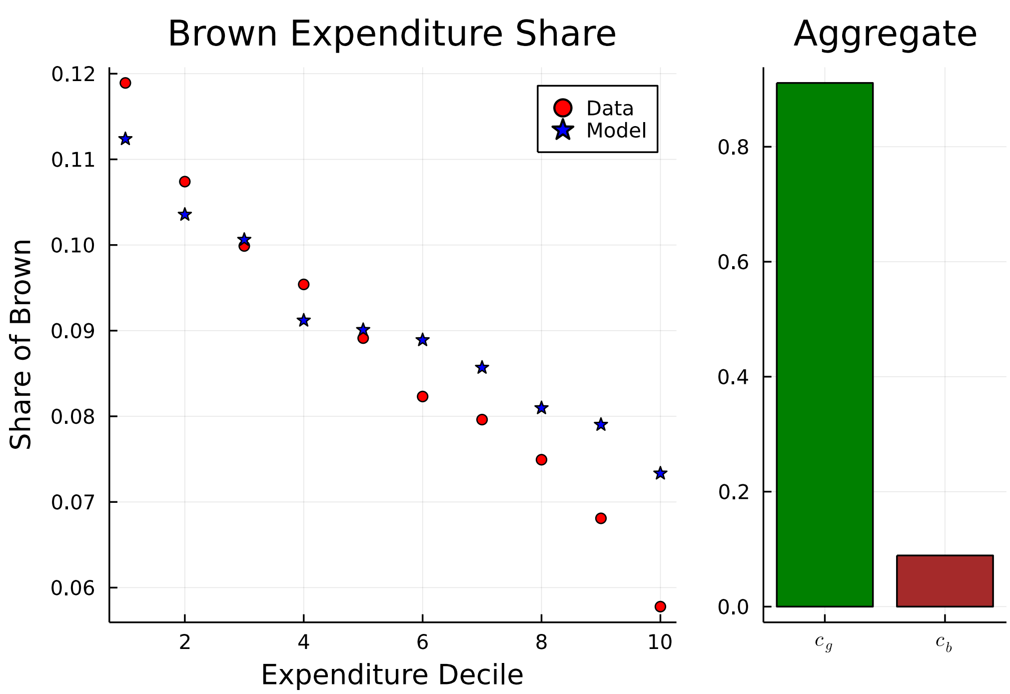

Figure 3. Baseline Model Fit

We are left with three parameters to estimate : the brown minimal consumption $\bar{c}$, the elasticity of substitution across goods α_θ, the weight of brown and green goods in the utility function (which sum to 1), $\omega_{G,\theta}$ and $\omega_{B,\theta}$. Let's consider the set of estimated parameters $p = (\bar{c}, \alpha_\theta, \omega_{B,\theta})$, m_k the $k = 1...11$ moments we try to match, and $\hat{m}_k\left(p\right)$ the model-generated k-moment when the parameters are p. The estimated parameters are then the solution to:

$$\min_p \sum_{k=1}^{11} \left(\hat{m}_k\left(p\right) - m_k\right)^2$$

We use the identity matrix to weigh the moments. The estimated parameters are provided in table 1, and the estimation results can be seen in Figure 3, where the stars indicate the model outcome for the estimated coefficients. The equilibrium of the model is the steady-state distribution of agents together with the equilibrium distribution of consumption. From this, we can derive the model counterpart of the moments of the data. The model does a good job in reproducing the decreasing share of consumption of brown goods over the income distribution. The fit is not perfect at the top decile. We are currently improving this fit by introducing an empirical weighting matrix in the estimation.

IV. Counterfactual scenarios

Given this estimation, we now perform a number of policy experiments to observe the change in consumption inequality and total CO_2 emissions as measured by the overall consumption of brown goods. In the current iteration of the present paper, these experiments are performed in partial equilibrium to observe the change in the equilibrium distribution of agents – this restriction will be lifted in future revisions. More precisely, we compute the equilibrium distribution of the heterogeneous-agent model for each parameter change. Figure 4 plots the long-run effect of an increase the price of brown good by 15%, which can be seen as an increase of a carbon tax by 15%.

On can observe that the whole share of brown good consumption decreases by roughly 10 %. The right-hand side of the figure also shows that the consumption of green goods decreases because of a negative uncompensated wealth effect, which is due to an increase in prices.

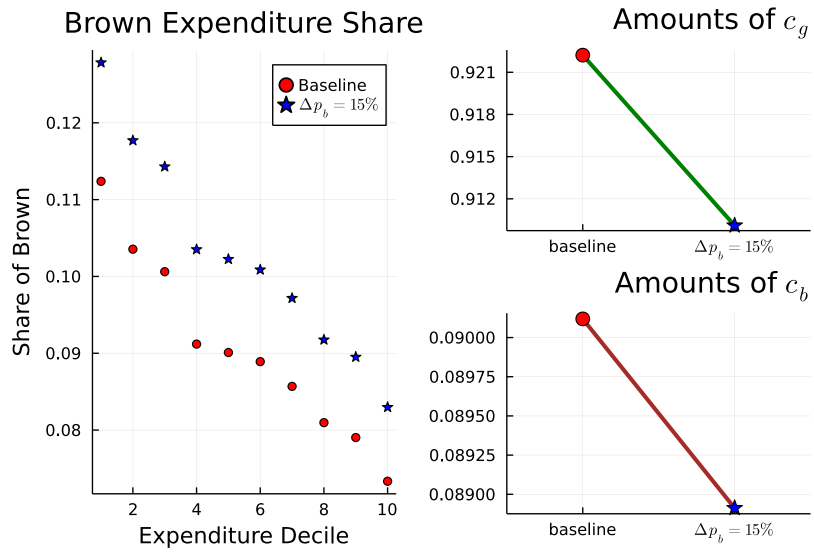

FIGURE 4. INCREASING THE BROWN GOOD PRICE BY 15%.

Next, we focus on decreasing the price of the green good by 15 %. Interestingly, the effect is very different as the distribution of brown good expenditure barely changes. This is due the fact that all expenditure deciles increase their consumption of green goods in equal proportion. This asymmetry between the change in price of the green and brown goods stems from the existence of a minimal consumption need for brown goods, $\bar{c}$, which is necessary to reproduce the empirical decreasing share of brown goods as a function of income.

Our final experiment is a decrease in wage by 15%, presented in Figure 6. This last experiment simulates an increase in labor tax to finance some public investment to mitigate the effects of carbon emissions. This results in an overall increase in the share of brown consumption, which is due a bigger fall in the consumption of green goods relative to brown goods, as can be seen at the right of the Figure. This outcome is again a direct consequence of the minimum consumption of brown goods, which makes its consumption less revenue elastic.

These first experiments show that households in the income distribution are heterogeneously affected by price change. The next step will be to define an

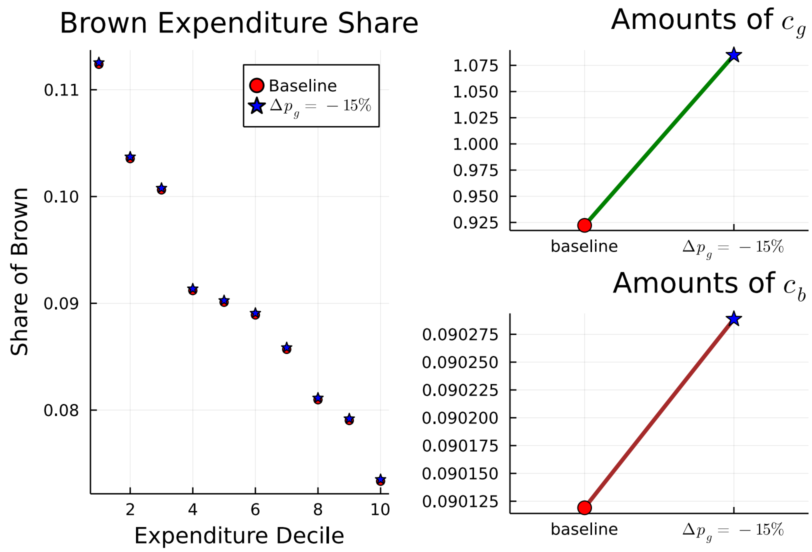

FIGURE 5. DECREASING THE GREEN GOOD PRICE BY 15%.

additional fiscal policy instrument to reduce the adverse effect of the increase in the price of carbon at the bottom of the distribution.

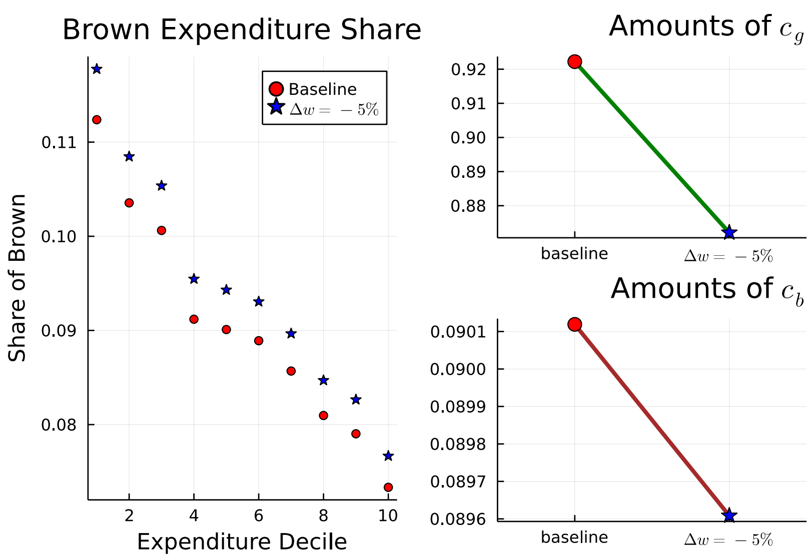

Figure 6. Decreasing the wage by 5%.

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Appendices

Full model specification

$$
\begin{aligned}
P_t^{mod} &= p_{G,t}\left(1+\left(\frac{\omega_{G,\theta}}{\omega_{B,\theta}}\right)^{\frac{1}{\alpha_\theta-1}}\left(\frac{p_{B,t}}{p_{G,t}}\right)^{\frac{\alpha_\theta}{\alpha_\theta-1}}\right)\\
T_t^{mod} &\equiv T-p_{B,t}\left(\bar{c}_{B,\theta}-\left(\frac{p_{B,t}\omega_{G,\theta}}{p_{G,t}\omega_{B,\theta}}\right)^{\frac{1}{\alpha_\theta-1}}\bar{c}_{G,\theta}\right)
\end{aligned}
$$

- Unconstrained agents

$$
\begin{aligned}
\left(c_{G,t}-\bar{c}_{G,\theta}\right)^{-\sigma} &= \beta\mathbb{E}\left(1+r_{t+1}\right)\left(c_{G,t+1}-\bar{c}_{G,\theta}\right)^{-\sigma}\\
P_t^{mod}c_{G,t}+a_{t+1} &= (1+r_t)a_t+w_t y+T_t^{mod},
\end{aligned}
$$

- Constrained agents

$$
\begin{aligned}
a_{t+1} &= \bar{a}\\
P^{mod}c_{G,t} &= (1+r_t)a_t+w_t y+T_t^{mod},
\end{aligned}
$$

$$\int a\,d\Lambda_t = K_t, \tag{A1}$$

$$\int c_B\left(a\right)d\Lambda_t = C_{B,t} \tag{A2}$$

$$\int c_G\left(a\right)d\Lambda_t = C_{G,t} \tag{A3}$$

$$C_{G,t}+I_{G,K,t} = Y_{G,t}, \tag{A4}$$

$$C_{B,t}+I_{B,K,t} = Y_{B,t}, \tag{A5}$$

$$T_t = \tau^c_{G,t}\tilde{p}_{G,t}C_{G,t}+\tilde{p}_{B,t}\tau^c_{B,t}C_{B,t}$$

$$\bar{K}_{t-1} = K_{B,t} + K_{G,t}$$
$$\bar{L} = L_{B,t} + L_{G,t},$$
$$C_{G,t} + I_{G,t} = Y_{G,t},$$
$$C_{B,t} + I_{B,t} = Y_{B,t}.$$
$$Y_{B,t} = A_{B,t} K_{B,t}^{\alpha_B} L_{B,t}^{1-\alpha_B}$$
$$Y_{G,t} = A_{G,t} K_{G,t}^{\alpha_G} L_{G,t}^{1-\alpha_G}$$
$$\tilde{r}_t = \alpha_G \tilde{p}_{G,t} A_{G,t} K_{G,t}^{\alpha_G - 1} L_{G,t}^{1-\alpha_G} - \delta = \alpha_B \tilde{p}_{B,t} A_{B,t} K_{B,t}^{\alpha_s - 1} L_{B,t}^{1-\alpha_s} - \delta$$
$$\tilde{w}_t = (1-\alpha_G) \tilde{p}_{G,t} A_{G,t} K_{G,t}^{\alpha_s} L_{G,t}^{-\alpha_G} = (1-\alpha_B) \tilde{p}_{B,t} A_{B,t} K_{B,t}^{\alpha_s} L_{B,t}^{-\alpha_B}$$

$$\begin{aligned} I_t &= \left(\omega_{G,K} I_{G,t}^{\alpha_K} + \omega_{B,K} I_{B,t}^{\alpha_K}\right)^{\frac{1}{\alpha_K}} \\ \bar{K}_t &= I_t + (1-\delta)\,\bar{K}_{t-1} \end{aligned}$$

$$I_{G,t} = \left(\frac{\tilde{p}_{G,t}}{\omega_{G,K}}\right)^{\frac{1}{\alpha_K - 1}} I_t \text{ and } I_{B,t} = \left(\frac{\tilde{p}_{B,t}}{\omega_{B,K}}\right)^{\frac{1}{\alpha_K - 1}} I_t$$

$$1 = \omega_{G,K}^{\frac{1}{1-\alpha_K}} \tilde{p}_{G,t}^{\frac{\alpha_K}{\alpha_K - 1}} + \omega_{B,K}^{\frac{1}{1-\alpha_K}} \tilde{p}_{B,t}^{\frac{\alpha_K}{\alpha_K - 1}}$$

$$\begin{aligned} S_t &= m Y_{B,t-1} + S_{t-1}(1-d_m). \\ A_{B,t} &= A_{0,B} A_t \left(1 - D_s(S_t)\right) \\ A_{G,t} &= A_{0,G} A_t \left(1 - D_s(S_t)\right) \\ 1 - D_s(S_t) &= e^{-\gamma_s (S_t - \overline{S})}, \end{aligned}$$