On the Geographic Implications of Carbon Taxes*

Bruno Conte
Università di Bologna

Klaus Desmet
SMU

Esteban Rossi-Hansberg
University of Chicago

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Abstract

Using a multisector dynamic spatial integrated assessment model (S-IAM), we argue that a carbon tax introduced by the European Union (EU) and rebated locally can, if not too large, increase the size of Europe's economy by concentrating economic activity in its high-productivity non-agricultural core and by incentivizing immigration to the EU. The resulting change in the spatial distribution of economic activity improves global efficiency and welfare. A carbon tax introduced by the US generates similar effects. This stands in sharp contrast with standard models that ignore trade and migration in a world shaped by economic geography forces.

*Conte: Università di Bologna and CESifo, b.conte@unibo.it, Desmet: Department of Economics, Cox School of Business, Southern Methodist University, NBER and CEPR, kdesmet@smu.edu, Rossi-Hansberg: Department of Economics, University of Chicago, NBER and CEPR earossih@uchicago.edu.
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1 Introduction

Global carbon taxes have long been heralded as the best solution to combat climate change. The logic is straightforward: they help bridge the gap between the private and the social cost of carbon, caused by the negative effects of carbon-induced climate change. Unfortunately, global agreements on climate policy have not been easy to forge. Instead, climate policy has mostly progressed through local, national, and sometimes regional unilateral initiatives. Unilateral policy, however, has the obvious drawback of generating economic and carbon leakage by shifting production and emissions to areas where carbon is taxed less, or not at all. Unilateral carbon taxes therefore seem, at first glance, costly in the short run due to the implied distortion, and ineffective in the long run due to the implied leakage.

In this paper, we argue that this reasoning is incomplete and misleading because it ignores how unilateral carbon taxes interact with the forces that shape the economic geography of the world. We show that the spatial response to a unilateral carbon tax can lead to a local expansion of the region introducing the tax and to global welfare gains. Politicians typically worry that a unilateral carbon tax might lead to a shrinking of their economy or a dislocation of their industrial sector. In our quantitative evaluation of a unilateral carbon tax introduced by either the European Union or the United States, we show not only that these worries are exaggerated, but that global efficiency may be enhanced in the wake of such a tax.

Carbon taxes affect primarily industries that use energy intensively. For example, firms in the manufacturing sector tend to be more energy-intensive than in agriculture. Hence, because sectoral specialization exhibits large variation across space, a uniform tax within a region will affect some locations significantly more than others. This heterogeneity in the size of the effective tax will naturally lead to reallocation across space. In an economy with trade and migration where the spatial distribution of economic activity is driven by agglomeration economies and other externalities, this reallocation can trigger a host of indirect effects. In particular, it can improve the efficiency of the spatial allocation and result in overall welfare gains. Hence, under certain circumstances, unilateral carbon taxes can improve global welfare by bringing the spatial distribution of economic activity closer to the efficient equilibrium. This positive effect occurs even in the short run, when the impact on climate change is negligible.

Because global warming has different effects across locations, sectors, and time, evaluating the effects of a carbon tax requires a high-resolution multi-sector dynamic spatial integrated assessment model (S-IAM). Our quantitative model, based on Conte et al. (2021), features a realistic world economy divided into more than 17,000 locations with positive land mass. Firms in multiple sectors can improve their technology by innovating, and sell their products around the world subject to trade costs. Agents work, consume a basket of products, and have the possibility of migrating between locations subject to moving costs. Production uses energy that leads to carbon emissions, which accumulate in the atmosphere, causing global warming. As temperatures rise, they affect firm productivity differentially across sectors. In this model, a carbon tax affects the geography of absolute and comparative advantage, because sectors differ in their energy intensity and because it mitigates global warming. The rebating of the revenue of a carbon tax further impacts relative income across space. In response, migration and trade patterns adjust. Locations that gain population benefit from both static and dynamic agglomeration economies. As the economic geography changes due to a carbon tax, the spatial equilibrium may become more or less efficient, hence impacting welfare positively or negatively.

Our quantitative policy analysis focuses mainly on the European Union (EU), though we show very similar results for a carbon tax introduced by the US. From a policy point of view, the EU is a natural choice, because it is perhaps the region of the world that has been most active in introducing a region-wide tax on carbon (or, equivalently, a carbon trading system). Our evaluation predicts that a hypothetical uniform carbon tax of 40 US\$/tCO_2 introduced by the EU and rebated locally can increase the size of the EU economy by further concentrating economic activity in its high-productivity non-agricultural core and by attracting more immigrants to Europe. This, in turn, leads to a more efficient global distribution of population, so that world welfare improves. Understanding this result requires exploring the spatially heterogeneous effects of a carbon tax on local sectoral specialization and on the spatial distribution of economic activity.

Because non-agriculture is more intensive in energy than agriculture, we might have expected an EU carbon tax to weaken Europe's comparative advantage in non-agriculture, leading to a relative drop in non-agricultural output.[1] If carbon tax revenues

[1]The higher incidence of a carbon tax in non-agriculture depends on it being limited to CO_2. If we were to take into account emissions from other greenhouse gases, such as methane (CO_4) and nitrous oxide (N_2O), agriculture would face a greater incidence than non-agriculture. We return to this

were lost, this is indeed what would happen: the increase in the relative price of non-agricultural goods would cause a relative decline of non-agriculture in Europe. The EU would shrink, and global welfare would decline. However, when carbon tax revenue is locally rebated, the results are reversed. Because output is traded, the higher relative tax burden in non-agriculture is only partly passed on to wages. Once local rebating is added, regions specializing in non-agriculture experience a relative gain in income. We formally prove how the introduction of a carbon tax in a single location can generate a positive income effect on its economy. In the case of the EU, this type of income effect generates migration from agricultural to non-agricultural regions, causing non-agricultural output to increase relative to agricultural output. This effect is further amplified by agglomeration forces.

As Europe's non-agricultural core grows, the EU attracts more immigrants, and its economy becomes larger. Although real income per capita in the EU drops, the reallocation of population and economic activity improves global efficiency and welfare. This suggests that in the absence of a carbon tax there is too little geographic concentration in the EU core and there are too few people in Europe. As such, an EU carbon tax with local rebating acts as a place-based policy that subsidizes Europe's non-agricultural core and attracts more people to move to the European Union. The importance of these results cannot be overstated: not only does a unilateral EU carbon tax lower global carbon emissions, thus mitigating the warming of the planet, it also increases Europe's weight in the world economy and it improves global welfare and efficiency. When carbon taxes increase above $\sim$55 US$ per tCO_2, the distortions generated by the tax start to dominate and the EU economy shrinks, although global welfare gains continue for relatively high levels of carbon taxes. Regardless, even for higher carbon taxes, the contraction of the EU economy would be smaller than when ignoring spatial forces.

These findings show that using a spatial integrated assessment model (S-IAM) is essential if we want to correctly quantify the economic effects of a carbon tax. Rather than simply imposing a distortionary cost, an EU carbon tax with local rebating corrects a pre-existing spatial inefficiency that would be ignored in a model without the forces that determine the geography of economic activity. One could argue that changes in migration policy would be a more direct way of improving global welfare, or that first-best taxes and subsidies that are heterogeneous across space would be more effective

discussion in the quantification section.

at strengthening Europe's non-agricultural core. However, in practice, no such spatially heterogeneous tax and subsidy scheme is currently on the table, while an EU-wide carbon tax is. In that sense, our contribution should be viewed as a policy-relevant evaluation where we show that a modest unilateral carbon tax can be globally welfare-improving, while locally expanding the size of the economy.

In addition to this key result, our assessment provides comprehensive and detailed insights into how an EU carbon tax with local rebating reshapes the world's economic geography. Apart from reinforcing the EU's non-agricultural core, we see southern Europe, Scandinavia, and southeastern Europe move more into agriculture. Over time, these patterns are reinforced in southern Europe, where future agricultural productivity is enhanced by a carbon tax that limits global warming. The opposite occurs in Scandinavia, where less warming depresses agricultural yields. Regions bordering the EU, such as Great Britain, benefit from an industrial revival, as the EU grows and its periphery specializes in agriculture. Outside the EU, the developed world expands, whereas the developing world shrinks, as more people move to high-income countries.

A consequential policy choice in our model is how the revenue of a carbon tax is rebated. A key driver of the welfare-improving effect of a unilateral carbon tax is that it acts as a subsidy to the spatial agglomeration of economic activity in Europe. That result depends crucially on the local rebating scheme generating a positive income effect in the EU core. To see how sensitive our results are to this type of rebating, in the Appendix we consider several alternatives.[2] First, if revenues of a carbon tax are rebated to the EU population on a per-capita basis, the income effect in the EU core is smaller, and the global welfare gains are more limited. A carbon tax of 40 US$ per tCO_2 no longer expands the size of the EU economy, though a lower carbon tax still does. Second, if revenues are rebated to the developing world, fewer migrants move to Europe, and its economy shrinks. By keeping more people in low-productivity places, global efficiency and welfare drop. In contrast, spatial inequality across the globe falls, as income per capita drops in Europe and rises in sub-Saharan Africa.

The mechanisms we uncover are not specific to the EU case. We illustrate this by considering what would happen if the unilateral carbon tax of 40 US$/$tCO_2$ were to be introduced in the US, rather than in the EU. Both qualitatively and quantitatively,

[2] The initial allocation of emission allowances in the context of the EU Emissions Trading Scheme (ETS) was similar to local rebating: by basing the allocation on historic emissions, it amounted to redistributing the value of these allowances to the most carbon-intensive locations.

the results are similar, once we account for each region's unique specialization patterns in space. This should probably not come as a surprise: the economies of the US and the EU are similar in size and productivity, and both have comparative advantage in non-agriculture. We know that a carbon tax with local rebating redistributes income to the regions specialized in the energy-intensive non-agricultural sector. In both the US and the EU, this implies that income is redistributed toward dense, high-productivity areas. Since this attracts migrants toward high-efficiency locations, we see the same type of global welfare gains when the US introduces a carbon tax.

Our work is related to a large literature on the climate and welfare effects of carbon taxes. Because carbon emissions cause a global externality, a central result of this literature is that carbon taxes are most effective if adopted by a large part of the world. That is why many models have focused on quantifying the optimal global carbon tax (Nordhaus, 2010; Golosov et al., 2014; Hassler et al., 2016, 2018). However, those papers ignore the complex forces that shape the world's economic geography. Our paper shows that taking these forces into account is key, hence the need for introducing space into standard integrated assessment models. Weisbach et al. (2022) and Kortum and Weisbach (2021) do consider carbon leakage and other forces when analyzing unilateral carbon policy in a multi-country economy, but they do not allow for geographic factor mobility, nor do they incorporate agglomeration economies.

An important question within the optimal carbon tax literature deals with the possible presence of other distortionary taxes. In a first-best world, standard Pigouvian logic implies that carbon should be taxed to compensate for its social cost (Golosov et al., 2014). However, in a second-best world where there are other distortionary taxes, the introduction of a carbon tax tends to compound pre-existing distortions, implying an optimal carbon tax below the Pigouvian level (Bovenberg and van der Ploeg, 1994; Bovenberg and de Mooij, 1994; Bovenberg and Goulder, 1996; Barrage, 2020). Although our paper does not focus on the optimal level of carbon taxes, it has the presence of pre-existing inefficiencies in common with this literature.

Our central finding that carbon taxes may improve global efficiency is reminiscent of the double-dividend hypothesis in the environmental taxation literature. If the revenues from carbon taxes are used to lower other pre-existing distortionary taxes, rather than simply being rebated lump-sum, there might be a double gain: not only does pollution decline, but efficiency also improves. However, because a carbon tax typically magnifies pre-existing distortions, this double dividend has generally proven to be elusive. Although using revenues to lower other taxes does reduce the cost of a carbon tax, it typically does not turn that cost into a benefit (Goulder, 1995; Goulder et al., 1997).[3] In our paper, we do get a double dividend, not from reducing pre-existing distortionary taxes, but from correcting a pre-existing inefficient spatial allocation.

Our result that carbon taxes redistribute income toward energy-intensive non-agricultural regions is also related to policies aimed at affecting the terms of trade. In this context, Costinot et al. (2015) show that optimal export taxes are increasing in the degree of comparative advantage. The intuition is straightforward: if comparative advantage is strong, then raising the price of the exported good need not lead to a large decrease in the quantity exported, and hence benefits local producers. In our paper, a carbon tax has a similar effect of raising the local income in regions that export energy-intensive goods.[4] However, in contrast to standard trade models, this may improve the efficiency of the spatial equilibrium, leading to global welfare gains.

Our paper also speaks to the literature on the redistributive effects of carbon taxes. Because the poor tend to spend a larger share of their income on energy-intensive goods, a carbon tax tends to be regressive from the consumption side (Pizer and Sexton, 2019; Goulder et al., 2019). From the income side, the picture is more complex, as the redistributive effects of a carbon tax depend on the sector people work in, the way in which revenue is rebated, and the effect on the relative price of different factors of production (Rausch et al., 2011; Fullerton and Monti, 2013; Känzig, 2022). In addition to its redistributive effects on income groups, the literature has also studied how carbon taxes redistribute income across generations (Leach, 2009; Fried et al., 2018). In our paper, the redistributive effects of carbon taxes also play a central role, but the focus is on how it reallocates income across space.[5]

Our work further expands the growing literature that uses dynamic spatial integrated assessment models (S-IAM) to evaluate the economic impact of climate change. An early S-IAM in one-dimensional space is Desmet and Rossi-Hansberg (2015). Later

[3] The double-dividend concept has also been applied to other contexts, such as the use of anti-sprawl development taxes to lower pre-existing distortionary property taxes (Bento et al., 2011).

[4] Because carbon taxes act as a policy that restricts trade, this raises the possibility that governments might use carbon taxes as disguised protectionism. For a discussion, see Copeland (2000) and Maggi (2016).

[5] In a very different context, one paper that also deals with the spatial effects of a carbon tax is Khanna et al. (2021). They empirically show that in China skilled workers emigrate more in response to pollution than unskilled workers. In their setting, reducing pollution increases aggregate productivity by keeping the high-skilled in high-productivity cities.

S-IAMs in two-dimensional space include Desmet et al. (2018), Conte et al. (2021), Cruz and Rossi-Hansberg (2021) and Cruz (2021). Other papers in that vein are Nath (2020) and Conte (2022), though they are static. In addition, both ignore innovation, and the former ignores migration, as key adaptation strategies to climate change. Also noteworthy is Rudik et al. (2022) who use a multi-sector dynamic spatial model to analyze adaptation through trade and labor market reallocation in the US. Balboni (2021) is another relevant paper that looks at the specific case of flooding and infrastructure investment in Vietnam. Most of these papers do not focus on carbon taxes and policy. An exception is Cruz and Rossi-Hansberg (2021), though that model does not have multiple sectors and does not consider the possibility of unilateral carbon taxes implemented by a subset of the world economy. Cruz and Rossi-Hansberg (2022) do study unilateral carbon policy and the impact of the pledges in the Paris Agreement, but also ignore multiple sectors and the role of different rebating schemes.

The rest of the paper is organized as follows. Section 2 describes our model, discusses the local effects of carbon taxes, and summarizes the quantification. Section 3 presents the quantitative analysis of the EU carbon policy when the revenue of the tax is discarded. Section 4 shows that local rebating of the carbon tax can lead to an increase in the size of the EU economy and to global welfare gains. Section 5 analyzes the effects of a unilateral carbon tax in the US. Section 6 concludes. An Appendix gives the proof of our lemma, discusses alternative rebating schemes, provides additional tables and figures, and gives further details on solving the model.

2 Model, Data and Calibration

2.1 Model

We extend the dynamic spatial model of Desmet et al. (2018) and Conte et al. (2021) to allow for carbon taxes. This section gives a brief overview of the main elements of the model. We refer the reader to those papers for additional details.

Endowments and preferences. The economy occupies a two-dimensional surface S. A location is a point $r \in S$, with land density $H(r)$. Each of the $\bar{L}$ agents in the economy supplies one unit of labor.

An agent j who resides in location $r \in S$ in period t, and in locations $\{r_0, ..., r_{t-1}\}$ in the past, has utility

$$U_t^j\left(r_0,...,r_{t-1},r\right)=a_t\left(r\right)\prod_{i=1}^{I}\left[\int_0^1 c_{it}^{\omega}\left(r\right)^{\rho}d\omega\right]^{\frac{\chi_i}{\rho}}\varepsilon_t^j\left(r\right)\prod_{s=1}^{t}m\left(r_{s-1},r_s\right)^{-1} \tag{1}$$

in period t, where $a_t\left(r\right)$ is the level of local amenities, $c_{it}^{\omega}\left(r\right)$ is the consumption of variety ω of good i, $1/(1-\rho)$ is the elasticity of substitution between different varieties of the same good, χ_i is the share of good i in the agent's expenditure, $\varepsilon_t^j\left(r\right)$ is a location preference shock drawn from a Fréchet distribution with shape parameter $1/\Omega$, and $m\left(r_{s-1},r_s\right)$ is the flow cost of moving from r_{s-1} to r_s in period s.

This setup is characterized by two dispersion or congestion forces. First, locational preference heterogeneity implies that not everyone prefers the same location. The higher the value of Ω, the greater this preference heterogeneity, and hence the stronger this first spatial dispersion force. Second, local amenities are subject to local congestion. More specifically, $a_t\left(r\right)=\bar{a}\left(r\right)\left(\bar{L}_t\left(r\right)/H\left(r\right)\right)^{-\lambda}$, where $\bar{L}_t\left(r\right)$ denotes the agents residing in r. The higher the value of λ, the stronger this second dispersion force.

The cost of moving from r to s is the product of an origin-specific cost, $m_1\left(r\right)$, and a destination-specific cost, $m_2\left(s\right)$, so that $m\left(r,s\right)=m_1\left(r\right)m_2\left(s\right)$. Remaining in the same place is costless, and so $m\left(r,r\right)=m_1\left(r\right)m_2\left(r\right)=1$. This implies that the cost of leaving a location is the inverse of the cost of entering that location, i.e., $m_2(r)=m_1(r)^{-1}$. As a result, an immigrant only pays the flow utility while residing in the host location. This makes the decision to migrate fully reversible, simplifying an agent's forward-looking migration decision to a static one.

In addition to earning income from work, $w_t\left(r\right)$, an agent residing in r at time t gets a proportional share of local land rents, $R_t\left(r\right)H\left(r\right)/\bar{L}_t\left(r\right)$, as well as a proportional share of global profits from the resource extraction sector, $\Pi_t/\bar{L}$, and possibly a carbon tax rebate, $b_t(r)$. We can then define $u_t(r)$, the utility level associated with local amenities and real income as

$$u_t\left(r\right)=a_t\left(r\right)\frac{w_t\left(r\right)+\Pi_t/\bar{L}+R_t\left(r\right)H\left(r\right)/\bar{L}_t\left(r\right)+b_t(r)}{\prod_{i=1}^{I}P_{it}\left(r\right)^{\chi_i}}, \tag{2}$$

where P_{it} is the price index of sector i in location r, which we specify below. We use $u_t(r)$ as a measure of social welfare, though it does not include the idiosyncratic preferences of agents for a location nor any mobility costs agents might have incurred. The total nominal income of agents in a location can be written as

$$y_t(r)=w_t\left(r\right)\bar{L}_t(r)+\left(\Pi_t/\bar{L}\right)\bar{L}_t(r)+R_t\left(r\right)H\left(r\right)+b_t(r)\bar{L}_t(r). \tag{3}$$

Technology. A firm producing variety ω in sector i in location r at time t uses a production function given by

$$q_{it}^{\omega}(r) = L_{\phi,it}^{\omega}(r)^{\gamma_i} z_{it}^{\omega}(r) L_{it}^{\omega}(r)^{\mu_i} E_{it}^{\omega}(r)^{\sigma_i} H_{it}^{\omega}(r)^{1-\gamma_i-\mu_i-\sigma_i}, \tag{4}$$

where $q_{it}^{\omega}(r)$ denotes the firm's output, $L_{\phi,it}^{\omega}(r)$ is innovation labor, $L_{it}^{\omega}(r)$ is production labor, $E_{it}^{\omega}(r)$ is energy use, $H_{it}^{\omega}(r)$ is land use, and $z_{it}^{\omega}(r)$ is an idiosyncratic productivity shifter drawn from a Fréchet distribution with c.d.f. $Pr\left[z_{it}^{\omega}(r) \leq z\right] = e^{-(Z_{it}(r)/z)^{\theta}}$ and $\theta > 0$. The average productivity of good i in location r at time t, $Z_{it}(r)$, is given by

$$Z_{it}(r) = \tau_{it}(r)\, g_i(T_t(r)) \left(\bar{L}_{it}(r)/H_{it}(r)\right)^{\alpha_i}, \tag{5}$$

where $\tau_{it}(r)$ denotes the location's fundamental productivity in sector i at time t, $g_i(\cdot)$ is a sector-specific temperature productivity discount factor, $T_t(r)$ denotes temperature in r at time t, and $\bar{L}_{it}(r)$ is total sectoral employment, $L_{\phi,it}(r) + L_{it}(r)$. We assume that $\alpha_i > 0$ so average productivity is increasing in local density, $\bar{L}_{it}(r)/H_{it}(r)$. Hence, sectoral productivity benefits from local agglomeration economies. The higher the value of α_i, the stronger these sectoral agglomeration economies. A location's fundamental productivity in sector i evolves according to

$$\tau_{it}(r) = L_{\phi,i,t-1}(r)^{\gamma_i} \left[\int_S e^{-\aleph dist(r,s)} \tau_{i,t-1}(s)\, ds\right]^{1-\delta} \tau_{i,t-1}(r)^{\delta}, \tag{6}$$

where $dist(r,s)$ denotes the geographic distance between locations r and s. A location's fundamental productivity in sector i depends on local past sectoral innovation, local past sectoral productivity, and the spatial diffusion of past sectoral productivity from all other locations. Note that there is a dynamic agglomeration effect whereby more innovation today leads to more population and a larger market, and therefore more innovation tomorrow. The sector-specific temperature discount factor is bell-shaped in temperature, so

$$g_i(T_t(r)) = \exp\left[-\frac{1}{2}\left(\frac{T_t(r) - g_i^{opt}}{g_i^{var}}\right)^2\right] \tag{7}$$

where g_i^{opt} denotes the optimal temperature in sector i, and g_i^{var} is a parameter that determines the variance of the bell-shaped relationship between temperature and productivity in sector i.

Firms pay an ad-valorem tax $\Upsilon_t(r)$ on energy expenditure. Because there is a fixed relationship between energy use and carbon emissions, this tax can be interpreted as a carbon tax. Firms are perfectly competitive. Taking all prices and the carbon tax rate as given, a firm producing variety ω of good i chooses its inputs, and therefore its innovation rate, to maximize its static profits

$$p_{it}^{\omega}(r,r)\, q_{it}^{\omega}(r) - w_t(r)\left[L_{\phi,it}^{\omega}(r) + L_{it}^{\omega}(r)\right] - (1+\Upsilon_t(r))\, e_t E_{it}^{\omega}(r) - R_t(r)\, H_{it}^{\omega}(r) \tag{8}$$

subject to the production function (4), where e_t denotes the global price of energy and $p_{it}^{\omega}(r,r)$ is the price of variety ω of good i produced and sold in r. Firms maximize static profits because land markets are competitive and any local investment in innovation becomes available to all potential entrants next period. In order to win the competition for land, they optimally choose to innovate, leading to growth in local technology (Desmet and Rossi-Hansberg, 2014; Desmet et al., 2018). All rents from innovation then go to land, which is the only fixed local factor of production.

Energy supply. The world supply of energy is exogenously given by $E_t = e_t^{\varphi}$, where $\varphi \in (0,1)$. We ignore resource extraction costs, so that profits are equal to revenue in the energy sector, $\Pi_t = e_t E_t = e_t^{1+\varphi}$.

Carbon cycle and temperature. Carbon emissions caused by the use of energy add to the atmospheric stock of carbon according to

$$K_t = \varepsilon_1 K_{t-1} + \varepsilon_2 E_{t-1}, \tag{9}$$

where $\varepsilon_1 \leq 1$ determines how the carbon stock decays over time, and ε_2 determines how energy use generates carbon emissions that are added to the stock of carbon. Global temperature T_t at time t then evolves with the carbon stock according to

$$T_t = T_{t-1} + \nu\left(K_t - K_{t-1}\right), \tag{10}$$

where $\nu > 0$. Changes in global temperatures have heterogeneous effects across space,

$$T_t(r) = T_{t-1}(r) + \left(T_t - T_{t-1}\right)\xi(r), \tag{11}$$

where $\xi(r)$ are location-specific downscaling parameters that map changes in global temperature into changes in local temperatures.

Jurisdictions and governments. A jurisdiction J is a set of locations $r \in J$ with a government that sets carbon taxes. Each location r belongs to one jurisdiction and therefore has one government that collects carbon taxes. Government revenues from carbon taxes in location r are

$$A_t(r) = \sum_{i=1}^{I} \Upsilon_t(r) e_t E_{it}(r) = \sum_{i=1}^{I} \Upsilon_t(r) e_t \frac{\sigma_i}{\gamma_i + \mu_i} \frac{w_t(r)}{(1 + \Upsilon_t(r))\, e_t} \bar{L}_{it}(r) \tag{12}$$

where the second equality comes from the firm's profit maximization problem in sector i and location r. We consider two main schemes for how the government of jurisdiction J rebates carbon tax revenues. First, carbon tax revenues may be lost, in which case $b_t(r) = 0$. Second, carbon tax revenues may be rebated on a per-capita basis to the location that paid them, so $b_t(r) = A_t(r)/\bar{L}_t(r)$. In the Appendix, we discuss two additional rebating schemes. A first consists of carbon tax revenues of the jurisdiction being rebated on a per-capita basis to the jurisdiction's population, so $b_t(r) = \sum_{r \in J} A_t(r) / \sum_{r \in J} \bar{L}_t(r)$. A second consists of carbon tax revenues from jurisdiction J being paid out on a per-capita basis to a set of jurisdictions $\mathcal{J}$ that may or may not include J, so $b_t(r) = \sum_{s \in J} A_t(s) / \sum_{\mathcal{R} \in \mathcal{J}} \sum_{r \in \mathcal{R}} \bar{L}_t(r)$.

Prices and export shares. Under perfect competition, the price of a variety produced and consumed at r equals its marginal cost, $p^{\omega}_{it}(r, r) = \frac{mc_{it}(r)}{z^{\omega}_{it}(r)}$ where

$$\begin{aligned} mc_{it}(r) &= \gamma_i^{-\gamma_i} \mu_i^{-\mu_i} \sigma_i^{-\sigma_i} (1 - \gamma_i - \mu_i - \sigma_i)^{\gamma_i + \mu_i + \sigma_i - 1} \\ &\quad \times w_t(r)^{\gamma_i + \mu_i} e_t^{\sigma_i} (1 + \Upsilon_t(r))^{\sigma_i} R_t(r)^{1 - \gamma_i - \mu_i - \sigma_i}. \end{aligned} \tag{13}$$

The iceberg trade cost from r to s is denoted by $\varsigma(s, r)$. As in Eaton and Kortum (2002), trade is balanced location by location, so the spending of location s on sector-i varieties of location r as a share of its spending on sector-i varieties is given by

$$\pi_{it}(s, r) = \frac{Z_{it}(r)^{\theta} [mc_{it}(r) \varsigma(s, r)]^{-\theta}}{\int_S Z_{it}(u)^{\theta} [mc_{it}(u) \varsigma(s, u)]^{-\theta} du}. \tag{14}$$

The price index of sector i at location s is $P_{it}(s) = \bar{p} \left[\int_S Z_{it}(r)^{\theta} [mc_{it}(r) \varsigma(s, r)]^{-\theta} dr \right]^{-\frac{1}{\theta}}$ where $\bar{p} = \Gamma(1 - \frac{\rho}{(1-\rho)\theta})^{-\frac{1-\rho}{\rho}}$ with $\Gamma(\cdot)$ denoting the Gamma function.

Market clearing and equilibrium. Market clearing implies that the revenue of the firms producing varieties of good i at location r equals total spending on these varieties in the entire world. Market clearing for energy requires that worldwide revenues of the energy sector, $e_t^{1+\phi}$, equals worldwide spending on energy net of carbon taxes, $e_t \sum_{i=1}^{I} \int_S E_{it}(r)dr$. Hence, $e_t = \left[\sum_{i=1}^{I} \int_S \frac{\sigma_i}{\gamma_i+\mu_i} \frac{w_t(r)\bar{L}_{it}(r)}{1+\Upsilon_t(r)} dr\right]^{\frac{1}{1+\varphi}}$. Competitive labor and land markets also clear at all locations.

For a given period t and a given distribution of fundamental amenities $\bar{a}\,(r)$, productivities $\tau_{it}\,(r)$, temperatures $T_t\,(r)$, carbon tax rates $\Upsilon_t(r)$, and carbon revenue rebate schemes, utility maximization of agents, profit maximization of firms, and market clearing conditions determine the world price of energy e_t, profits in the energy sector Π_t, the distribution of population $\bar{L}_t\,(r)$, utility $u_t\,(r)$, amenities $a_t\,(r)$, land rents $R_t\,(r)$, wages $w_t\,(r)$, and carbon tax rebates $b_t\,(r)$ across locations, as well as the distribution of price indices $P_{it}\,(s)$ and employment $\bar{L}_{it}\,(r)$ across sectors and locations. The equilibrium conditions of period t, together with (6), yield the distribution of fundamental productivities in period $t+1$, $\tau_{i,t+1}\,(r)$. To update the distribution of temperature in $t+1$, $T_{t+1}\,(r)$, we use equations (9) to (11).

2.2 The Local Effect of Carbon Taxes

Our goal is to characterize the effect of carbon taxes on the distribution of economic activity and the resulting aggregate effect. To do so, it is useful to understand the direct and indirect effects that a carbon tax has on a particular location.

Consider first the case of a carbon tax $\Upsilon_t(r)$ on location r, where we throw away the tax revenue, so $b_t(r) = 0$. Given local wages and rents, equation (13) implies that the marginal cost of producers at r increases with an elasticity of σ_i with respect to the tax. According to equation (14), total expenditures on goods produced in r then decrease with an elasticity of θ relative to the increase in the marginal cost. The reduction in revenues, together with our Cobb-Douglas production function, implies that total income of agents in location r must decline. That is, local wages and rents fall. This partly offsets the increase in the marginal cost.[6] Because local income is lower, location r experiences out-migration. The magnitude of this out-migration depends on the elasticity of population to real income which is governed by Ω, the dispersion in idiosyncratic preferences (which is the inverse of the elasticity of migration to income). The lower Ω, the greater the out-migration, and the larger the drop in output. The falling population leads to smaller static and dynamic agglomeration effects on productivity, which amplify the effect, and

[6] If it were fully offset, then total demand for goods produced in r would be the same as before. However, because of the distortionary effects of the tax, production in r drops. With excess demand for goods produced in r, the marginal cost would increase above its original level.

smaller congestion forces which attenuate it. The end result is a smaller economy, with less people and less output.

Consider now the more complicated case when we rebate the carbon tax locally, so $b_t(r) = A_t(r)/\bar{L}_t(r)$. The same logic applies to this case, except that the decline in wages and rents does not necessarily lead to lower income and out-migration. Instead, since agents are getting the tax revenue as a rebate, the decline in wages and rents can be less than the rebate, leading to increases in income and in-migration. Whether income increases or not depends on the magnitude of the tax, as well as on the parameter values, in particular, θ and Ω. If the tax is large, its distortionary effect is large too, so that local wages and rents drop substantially. The magnitude of the decline depends on the trade elasticity, θ. The greater its value, the larger the reduction in local revenue. If the fall in income is big, it is not compensated by the tax rebate. This rebate amounts to the fraction of energy expenditures that are taxed rather than paid to energy producers outside the region. If local income drops even when considering the rebate, the location experiences out-migration, leading to a smaller population and a further reduction in output. The lower Ω, the larger this effect.

In contrast, if the tax is sufficiently small, the distortionary effect of the tax will be small. And if θ is low, the drop in income will be small. The rebate, which shifts income from energy suppliers to the local population, compensates this drop and leads to an increase in local income per capita. This attracts an inflow of workers, which attenuates the increase in the marginal cost induced by the carbon tax. Again, this last effect is stronger, the lower is the value of Ω. Hence, if the tax or θ are low enough, local population and output will grow, and these effects will be larger if Ω is small. As before, the expansion of the local economy is amplified by agglomeration effects, and attenuated by congestion forces. In sum, the effect of the tax on the local economy is positive but close to zero when the tax is negligible, grows as the tax increases, and then starts to decline, eventually turning negative, when the tax becomes large enough. The following lemma shows that a small carbon tax in a point in space generates an increase in local income and a corresponding rise in population.[7]

[7] Two technical conditions simplify the proof. First, the region implementing a carbon tax is "small" in the sense of not being able to affect the income of other regions and the price indices of any region (including its own). Second, the proof requires α_i to be sufficiently small. Since a carbon tax leads to a reallocation of factors of production across sectors, the relative productivity of sectors can change because of the existence of sector-specific agglomeration economies. Because this can have complex effects on wages and rents, assuming that α_i is sufficiently small effectively switches off this additional

Lemma 1 *Suppose the local government of a small region r imposes a carbon tax that is rebated lump-sum to the local population. If $\theta > 1$ and α_i is sufficiently small, there exists a strictly positive carbon tax that raises local income, and attracts migrants to the region.*

Proof. See Appendix A. ■

Perhaps surprisingly, the reasoning above implies that a local tax on carbon, if locally rebated, can have positive effects on local output and population. Intuitively, the incidence of the tax falls on all the trading partners of a location, including energy suppliers, but the rebate is only distributed among locals.[8] Hence, if the tax is not too distortionary, locals can command a higher total income, leading to in-migration and an expansion of the local economy. This is reminiscent of arguments on optimal tariffs. As in that literature, a location can change its terms of trade in a way that is beneficial to the local economy. Naturally, if we rebate the revenue in alternative ways that are not local, the effect on the local economy might go from positive with local rebating, to negative if the tax revenue is lost or redistributed uniformly everywhere. Furthermore, if the tax leads to a larger population and GDP, it will lead to higher productivity and more innovation. These static and dynamic agglomeration effects result in even larger increases in the size of the local economy.

Finally, note that a tax on carbon is effectively larger in industries that are intensive in energy; namely, industries with high σ_i. Because of local comparative advantage, this will lead to differences in the effective tax rate across locations. As such, a similar carbon tax leads to larger changes in population and output in regions that are more specialized in industries intensive in energy.

2.3 Data and Calibration

Data. We partition the world into 64,800 $1^\circ \times 1^\circ$ cells, and focus on two sectors, agriculture and non-agriculture. At that level of spatial resolution, our quantification

mechanism. To understand the positive income effect of a carbon tax for a given local population size, this simplifying assumption is not consequential. Of course, once we consider the migratory response to a positive local income shock, α_i does play a role. In fact, the greater the strength of the agglomeration economies, the more the migratory response gets magnified.

[8] This is similar to the case for an export tax in Costinot et al. (2015): exporters pass on the price increase to foreigners so the local economy gains. The effect is larger, the stronger is comparative advantage.

uses initial distributions of population, total output, agricultural output, temperature, and land. These data come from Nordhaus et al. (2006), IIASA and FAO (2012) and IPCC (2020). We also use estimates of bilateral transport costs between any two cells (Desmet et al., 2018).

Parameter values. The parameter values are given in Appendix Table B1 and come mostly from Conte et al. (2021). The carbon cycle parameters are calibrated to emissions consistent with the relatively pessimistic business-as-usual Representative Concentration Pathway (RCP) 8.5. More specifically, we set parameter values so that in the absence of carbon taxes, we get a 1200 GTC increase in the stock of carbon by the end of the 21st century and an increase in global temperature of 3.7°C by 2100. To parameterize the bell-shaped temperature discount function in agriculture, we rely on agronomy studies to estimate an optimal growing season temperature of 21.1°C (or an optimal average annual temperature of 19.9°C). We set the variance parameter of the agriculture discount so that only 0.1% of world agricultural production takes place in locations with a temperature discount factor below 0.01.[9] For non-agriculture, we calibrate the temperature discount to the observed relation between temperature and the model-generated non-agricultural productivity across grid-cells. This gives us an optimal temperature in non-agriculture of 10.5°C. Appendix Figure B1 shows the sectoral temperature discounts. As can be seen, productivity in non-agriculture is less sensitive to temperature relative to agriculture.

A few other parameter values are worth mentioning. First, global warming is heterogeneous across space. We use the location-specific downscaling parameters from Conte et al. (2021) which tell us how much temperature goes up in location r for a one-degree global increase in temperature. Second, our results depend crucially on energy use by sector. For agriculture, Schnepf (2004) estimates direct energy use as share of overall expenditure to be 5.2%. Figures of the Australian Bureau of Statistics for the period 1995-2010 report a figure of 3.4% (Australian Bureau of Statistics, 2021). Taking an average, we use 4%. For non-agriculture, we start with two estimates of the energy share of total GDP: 8% according to Grubb et al. (2018) based on data of 32 OECD countries for the period 1971-2012, and 5.6% according to King et al. (2015) based on data of 44 countries covering almost 95% of world GDP for the period 1980-2010. Combining these two estimates with our parameter values for the share of agriculture in

[9]We use this criterion since otherwise regions that produce some agriculture but have a large temperature discount given their currently low temperatures experience an implausibly large boom when temperatures rise.

world GDP (5.1%) and the energy share in agriculture (4%) yields an energy expenditure share in non-agriculture of, respectively, 8.2% and 5.7%. Taking an average, we use 7%.[10] This makes non-agriculture relatively more intensive in CO_2 emissions compared to agriculture.[11]

In the model simulations our baseline exercise investigates the impact of a hypothetical European Union-wide carbon tax of 40 US\$/tCO_2. As a reference, the average carbon tax in the four largest economies of the European Union is around 20 US\$/tCO_2. More specifically, it stands at 27 US\$/tCO_2 in Germany, 48 US\$ in France, 0 US\$ in Italy, and 16 US\$ in Spain (World Bank, 2022).[12] One unit of energy corresponds to emissions equal to ε_2 GTC, so that one ton of CO_2 corresponds to $1/(3.664 * \varepsilon_2 * 10^9)$ units of energy. Hence, $\Upsilon(r)e_0/(3.664 * \varepsilon_2 * 10^9 * \text{numéraire}) = 40$, where the model's numéraire is the level of average nominal wages in US\$ PPP of 2000. This gives us $\Upsilon(r) = \frac{40}{e_0} \times \frac{3.664 * \varepsilon_2 10^9}{\text{numéraire}} = 0.863$. This is the tax rate on energy spending that corresponds to a carbon tax of 40 US\$/tCO_2 in the first period of our simulation. We maintain this tax rate constant over time.

Solving and simulating the model. Using the initial distributions of land, total population, total output and agricultural output, together with the parameter values and the trade costs, we can back out the distributions of the initial fundamental productivities in agriculture and non-agriculture. We then use data on population and subjective well-being to determine the distribution of fundamental amenities. Moving costs are then set to match the model-predicted changes in population between 2000

[10] Alternatively, we could define non-agriculture to be industry. For the energy expenditure share in industry, Grave et al. (2016) estimate a weighted average of 7.7% across 14 manufacturing sectors for the year 2011, whereas the Australian Bureau of Statistics estimates an energy share in manufacturing of 6.4% for the period 1995-2010 (Australian Bureau of Statistics, 2021). This also gives an average of around 7%.

[11] Our focus is on a carbon tax on emissions coming from the use of fossil fuels. If we were to take into account emissions from other greenhouse gases, such as methane (CH_4) or nitrous oxide (N_2O), agriculture would become a relatively larger contributor to greenhouse gas emissions compared to non-agriculture. Following our logic, a more general greenhouse gas tax would act as a place-based policy that subsidizes Europe's agricultural periphery. When considering expanding the carbon tax to other types of emissions, policy makers should take into account that this might reverse some of our results, potentially increasing the cost of introducing a more general greenhouse gas tax.

[12] Until the beginning of 2021, the EU Emissions Trading System (ETS) also priced carbon at around 20 US\$/tCO_2. In general, any carbon tax is complementary to the ETS in the sense that sectors covered by the ETS are exempt from any additional carbon tax. Since the beginning of 2021, ETS carbon permits have soared to around 80 US\$/tCO_2. While we take 40 US\$/tCO_2 to be our baseline, we also show results for higher carbon taxes.

and 2005. Using the equilibrium allocation in period t, we can determine fundamental productivities and local temperatures in period $t+1$. This allows us to solve for sectoral employment levels, wages, and prices in $t+1$. Using this algorithm, we can simulate the model forward for as many periods as needed.

3 Carbon Taxes without Rebating

Starting in the year 2000, we simulate our model forward for 100 periods, until the year 2100. For the first 20 periods, there is no carbon tax anywhere. In 2021, the European Union introduces a unilateral tax rate on energy spending of $\Upsilon(r) = 0.863$, equivalent to a carbon tax of 40 US\$/tCO_2. In this section, we assess the spatial effects and the welfare impact of this carbon tax in the absence of rebating. While in practice it is unlikely that carbon tax revenues will be lost, we start with this evaluation because it will facilitate the understanding of our findings when we introduce alternative rebating schemes.[13]

Sectoral specialization. Figure 1 depicts, for different European countries, the percentage difference in agricultural and non-agricultural nominal output between the baseline with a carbon tax and a counterfactual exercise without such a tax. Upon impact, in 2021, the carbon tax has two effects. On the one hand, in the absence of rebating, the EU economy shrinks, leading to a drop in output across the board. On the other hand, the lower energy intensity of agriculture implies that comparative advantage in the EU shifts towards agriculture. Taking the two effects together, for the EU as a whole we see a larger output drop in non-agriculture (-3.44%) than in agriculture (0.86%). As for the UK, a border country outside the EU, the changing comparative advantage of its neighbor causes a drop in agricultural output and an increase in non-agricultural output. After the initial shock to comparative advantage, innovation allows countries to over time regain part of the lost output.

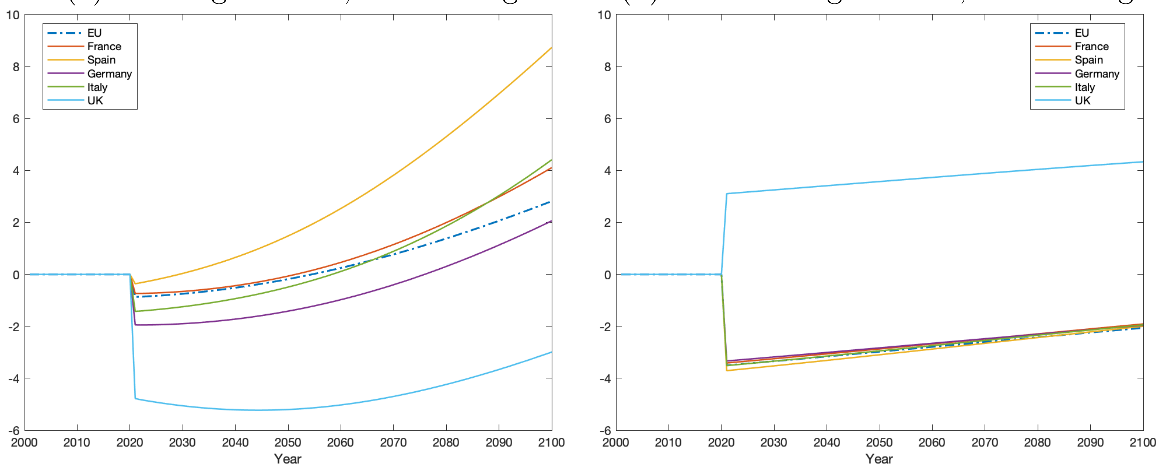
Figure 2 displays the change in sectoral output due to the carbon tax on a map of Europe and its neighbors in 2021 (top row) and 2100 (bottom row).[14] Upon impact,

[13] Of course, this exercise could also be interpreted as an analysis of the effect of an increase in a region's carbon price due to outside factors such as restrictions in world supply.

[14] In Panels (b) and (d) that display the change in non-agricultural output, a few cells exhibit very large percentage changes. These cells are characterized by discontinuities in the underlying data, either

Figure 1: Change in Sectoral Output Due to Carbon Taxes (No Rebating), Select Countries

(a) % Δ Agriculture, no rebating (b) % Δ Non-agriculture, no rebating



Note: Figure displays for different countries the log difference (*100) in nominal sectoral output between the baseline with carbon taxes (and no rebating) and a counterfactual without a carbon tax. Formally, for country C and sector i, it measures the difference in $100 * \log\left(\sum_{r\in\bar{C}} w_t(r)\bar{L}_{it}(r)\right)$ (which is a fixed share of nominal output) with and without carbon taxes. Panel (a) refers to agricultural nominal output, and Panel (b) to non-agricultural nominal output.

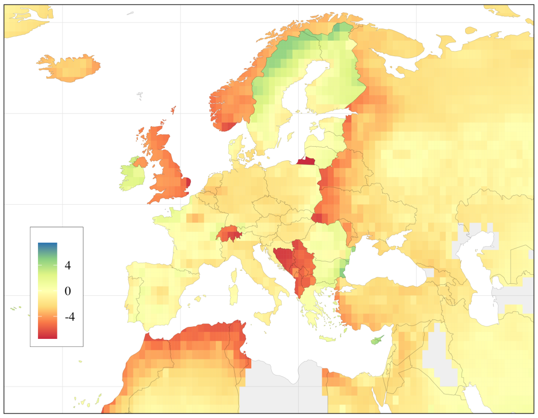
carbon taxes lower EU nominal output in both sectors, especially in non-agriculture, but there are some notable differences across regions (Panels (a) and (b)). Agriculture declines relatively less in the EU periphery than in its core. In fact, in Ireland, Sweden, Finland and Bulgaria, some areas see an increase in agricultural activity. Conversely, non-agriculture drops across the EU, but slightly less in the core. By the year 2100, Panel (c) shows that agriculture expands in the EU, especially in the southernmost peripheral regions, but not so in the northernmost peripheral regions. As the carbon tax limits the rise in temperature, this benefits more southern latitudes and hurts more northern latitudes. Non-agriculture partly recovers from the initial shock, though output is still lower than in a world without carbon taxes (Panel (d)).

As for regions neighboring the EU, they are affected by both the shrinking EU market and the gain in EU comparative advantage in agriculture. Both forces lead to a drop in agricultural activity in neighboring regions. In contrast, the two forces have opposite effects on non-agricultural output in neighboring regions. The maps show

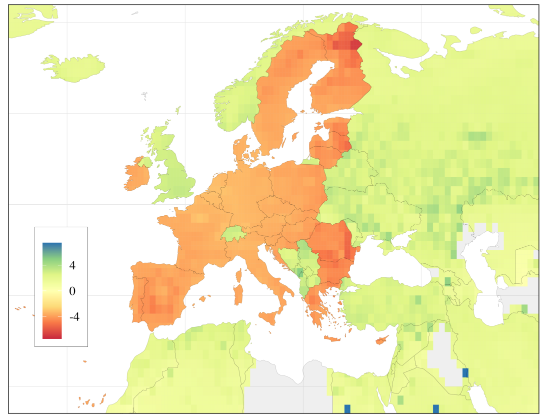
because they have almost no population or almost no non-agricultural output. The same discontinuities show up in some other maps, such as Figures D1 and D2.

Figure 2: Change in Sectoral Output Due to Carbon Taxes (No Rebating), Europe

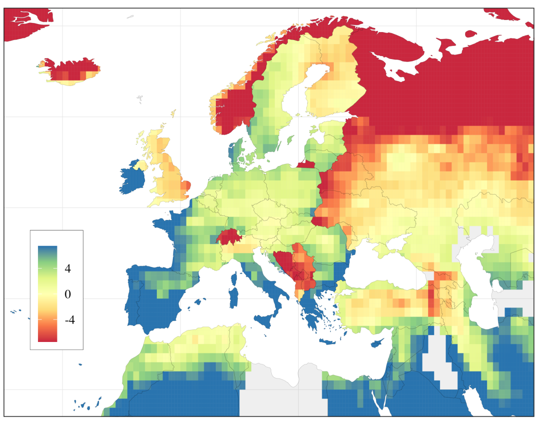
(a) % Δ Agriculture, no rebating, 2021



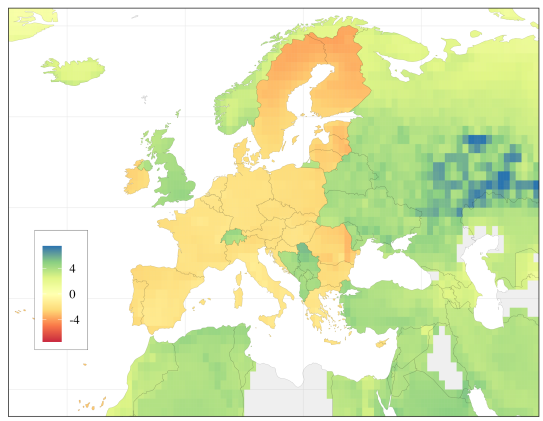
(b) % Δ Non-agriculture, no rebating, 2021



(c) % Δ Agriculture, no rebating, 2100



(d) % Δ Non-agriculture, no rebating, 2100

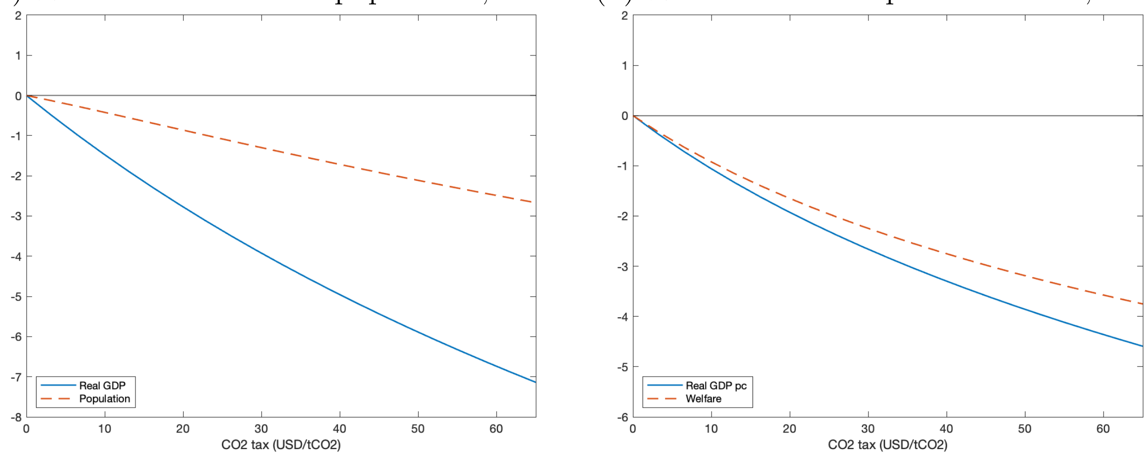


Note: Map displays for different countries the log difference in nominal sectoral output between the baseline with a carbon tax (and no rebating) and a counterfactual without a carbon tax. Panels (a) and (c) refer to agricultural nominal output, and Panels (b) and (d) to non-agricultural nominal output. Panels (a) and (b) are for 2021, whereas Panels (c) and (d) are for 2100.

that the shift in comparative advantage is more important: neighboring regions mostly experience an increase in non-agricultural output. For regions further afield, Appendix Figures D1 and D2 display similar maps for the entire world. The model-predicted numbers for different regions of the world are given in Appendix Table D1. Because of lower carbon emissions, global warming slows down. Focusing on 2100, this hurts agricultural output in regions that benefit from climate change, such as Siberia and Canada, and it helps agricultural output in regions that gain from less warming, such as South and East Asia.

Figure 3: Effect of Carbon Tax on EU Economy (No Rebating), 2021

(a) % Δ real income and population, 2021 (b) % Δ real income pc and welfare, 2021

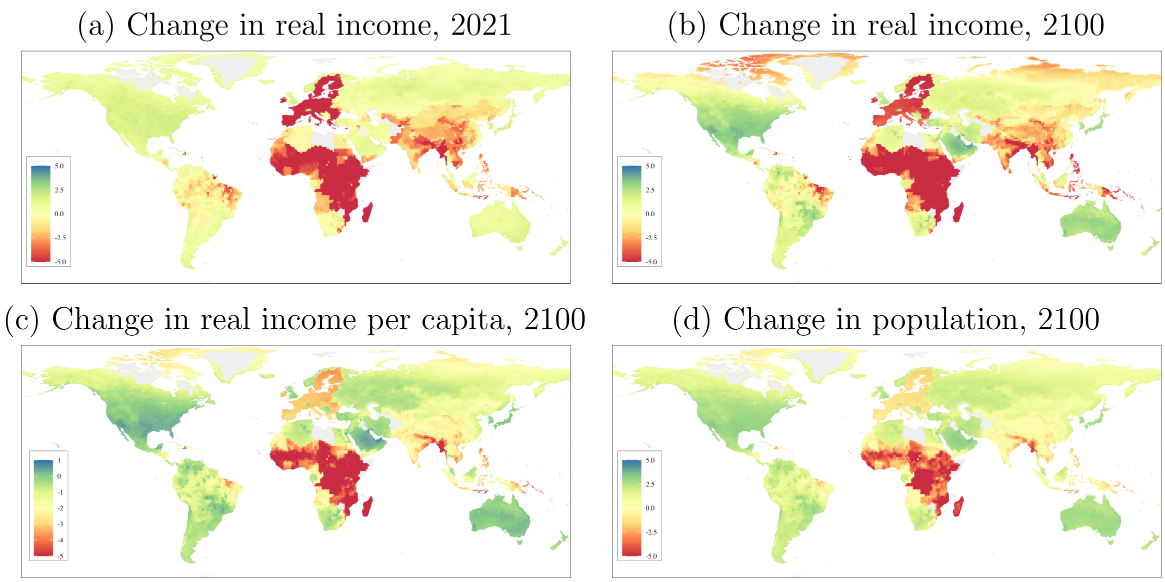


Note: For different EU variables, Figure displays the log difference (*100) in 2021 between the baseline with carbon taxes (and no rebating) and a counterfactual without carbon taxes. Panel (a) shows EU real income and population and Panel (b) shows EU real income per capita and welfare.

Real income, population and welfare for different tax levels. Figure 3 Panel (a) displays the change in real income and population in the EU in 2021 as a function of the level of the carbon tax. As expected, the higher the carbon tax, the more the EU economy shrinks. For a carbon tax of 40 US$/t$CO_2$, the drop in EU real income is 4.96% in 2021. This drop is due partly to the revenues of the carbon tax not being rebated, partly to the distortionary effects of the carbon tax, and partly to the drop in population. Panel (b) shows that a carbon tax makes the EU worse off at impact: real income per capita and welfare decline in 2021. For a carbon tax of 40 US$/t$CO_2$, the reduction in real income per capita in the EU is 3.3% in 2021 (Appendix Table D1). At a sectoral level, the shrinking of the EU economy is reflected in a decline in output in both agriculture and non-agriculture (Appendix D3 Panel (a)). Because EU comparative advantage is shifting toward agriculture, that drop is greater in non-agriculture. The change in comparative advantage also explains why in per capita terms, there is an increase in agricultural output and a drop in non-agricultural output (Appendix D3 Panel (b)).

Panels (a) and (b) of Figure 4 map the effect of carbon taxes on real income across the world for the years 2021 and 2100. As we already know, real income declines in the EU. Two forces determine which other regions of the world lose and which ones gain. On the one hand, regions with stronger comparative advantage in agriculture, such as

Figure 4: Effect of Carbon Tax on Real Income and Population across the Globe (No Rebating)



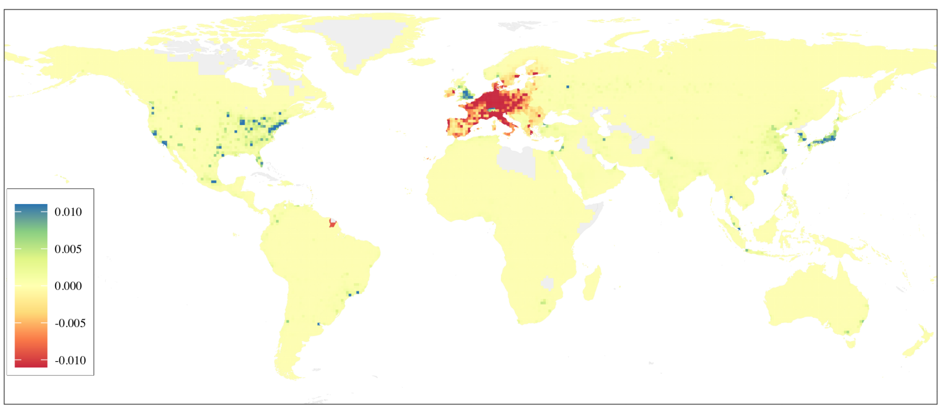
Note: Map displays for different variables the log difference (*100) between the baseline with carbon taxes (and no rebating) and a counterfactual without carbon taxes. Panel (a) shows real income in 2021, Panel (b) shows real income in 2100, Panel (c) shows real income per capita in 2100, Panel (d) shows population in 2100.

Brazil and sub-Saharan Africa, are more likely to lose, because the EU experiences a relative shift into agriculture. In contrast, regions that specialize in non-agriculture, such as North America, Australia and Japan, tend to gain. On the other hand, carbon taxes limit global warming over the next century, hurting areas closer to the poles and helping areas closer to the Equator. Consistent with this, in 2100 higher EU carbon taxes are expected to hurt northern Canada and northern Siberia, but benefit Mexico.

Panel (c) of the same figure shows which regions gain and which regions lose in terms of real income per capita in 2100 due to carbon taxes. North America, Australia, Argentina and Japan gain, whereas Europe, most of sub-Saharan Africa, parts of Brazil, and many regions of East Asia lose. Because carbon taxes mitigate global warming, northern Siberia and northern Canada also lose. More specifically, real income per capita in 2100 increases by 0.17% in the US and by 0.09% in Japan, and it declines by 2.36% in sub-Saharan Africa and by 1.35% in South and East Asia (see Appendix Table D1). Overall, the winners do not compensate for the losers: in the absence of rebating, global real income per capita declines by 0.63% in 2100. Population changes mirror real income per capita changes, as migration patterns adjust to changes in real income per capita (Panel (d)). Compared to a world without an EU carbon tax, in 2100 population is predicted to fall by 1.2% in the EU, by 3.56% in sub-Saharan Africa and by 0.2% in South and East Asia, whereas population is predicted to increase by 2.97% in the US (Appendix Table D1).

Emissions. Figure 5 shows a global map of the changes in emissions in 2021. We see that a carbon tax in the EU leads to a reduction in emissions in the EU, especially in the non-agricultural core and less so in the periphery. The overall drop in EU emissions in 2100 is 41%. Globally, emissions drop by almost 3% in 2100. The small drop of global emissions is partly the result of the size of the EU in the global economy but also of carbon leakage, by which production is shifted to other regions. The model predicts emissions in 2021 to increase by 12% in both the US and Japan. Though less apparent in the map due to the low base, emissions are also set to increase in sub-Saharan Africa (by 9%).

Figure 5: Effect of Carbon Tax on Emissions around the World (No Rebating), 2021



Note: Maps display differences in emission levels (in tCO_2) between the baseline with a carbon tax (and no rebating) and a counterfactual without a carbon tax. Figure D4 shows the equivalent European map.

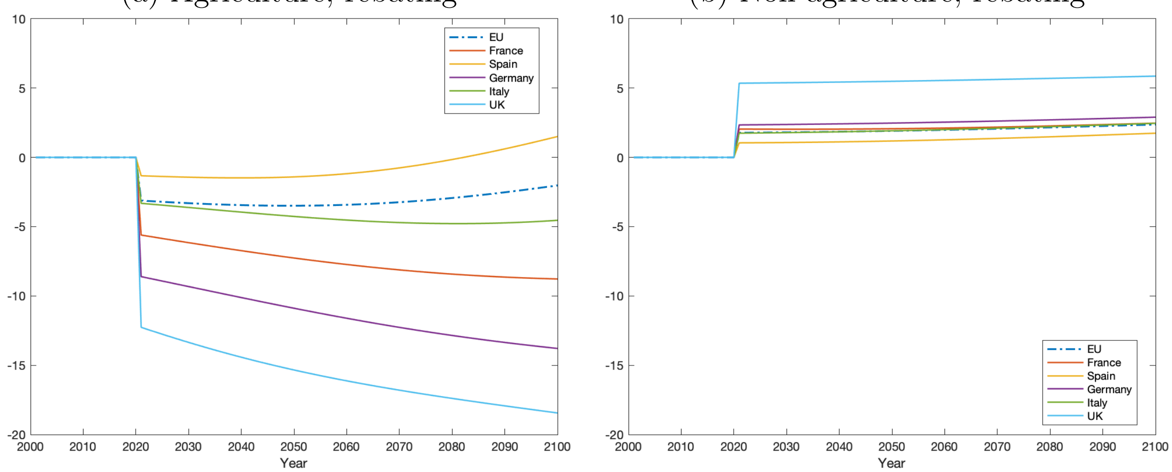
At the sectoral level, emissions in the EU drop in both agriculture and non-agriculture, because of the overall shrinking of the EU economy (Appendix Figure D5, Panel (a)). However, at the global level, emissions increase in agriculture but decrease in non-agriculture (Appendix Figure D5, Panel (b)). Given that Europe becomes more specialized in agriculture, we might have expected the carbon leakage in non-agriculture to be greater. However, several forces work in the other direction. First, non-agriculture is being displaced towards high-productivity regions, with therefore relatively low emissions per unit of output. Second, carbon taxes limit global warming, and reduce agricultural production in places such as Siberia that would acquire high agricultural productivity in the absence of carbon taxes. Instead, agriculture expands in less efficient areas, such as sub-Saharan Africa and parts of Asia.

4 Carbon Taxes with Local Rebating

We now proceed to analyze the case where the carbon tax revenue is rebated on a per-capita basis to the cell that paid the tax. Because the combination of taxes and rebates changes the spatial distribution of income, it has an impact on migration. And since the initial spatial distribution of economic activity is not efficient due to static and dynamic externalities, there is a possibility that this policy improves overall efficiency. In addition, since the carbon tax slows down global warming, it obviously also impacts output and welfare through that channel.

Figure 6: Change in Sectoral Output Due to Carbon Taxes (Local Rebating), Select Countries

(a) Agriculture, rebating (b) Non-agriculture, rebating



Note: Figure displays for different countries the log difference (*100) in nominal sectoral output between the baseline with carbon taxes (and local rebating) and a counterfactual without a carbon tax. Panel (a) refers to agricultural nominal output, and Panel (b) to non-agricultural nominal output.

Sectoral specialization. Non-agriculture is more energy-intensive, so it is harder hit by a carbon tax than agriculture. Because the direct effect of such a tax is a reduction of the EU's comparative advantage in non-agriculture, we would expect a relative drop in non-agricultural output. In fact, this is precisely what we saw in Figure 1. However, once we introduce local rebating, this result is reversed: Figure 6 shows that EU output in non-agriculture grows relative to agriculture. So how and why does local rebating change the result? Carbon taxes increase the relative price of non-agricultural goods, so that the higher carbon tax incidence in non-agriculture is not fully passed on to lower wages in regions specialized in non-agriculture. Once carbon tax revenue is rebated locally, these non-agricultural regions experience an increase in income per capita relative to the rest of the EU if the distortionary effect of the tax is not too strong (as we discussed in Section 2.2). This income effect generates migration from the agricultural regions to the non-agricultural regions of the EU. This effect is further magnified by agglomeration forces and moderated by congestion forces. As a result, we observe an increase in non-agricultural output, and a decrease in agricultural output.

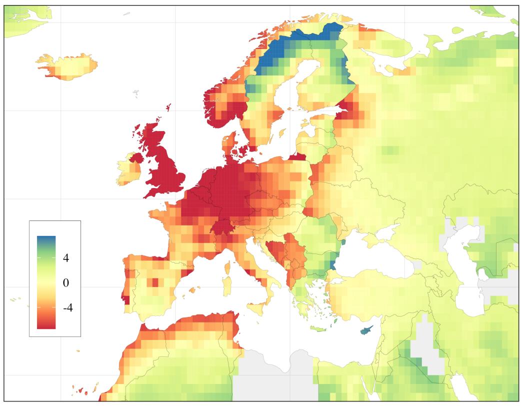
Because local rebating benefits the non-agricultural regions of the EU, it strengthens the core region of the union, in particular, the area covering Germany, the Benelux, northern and eastern France, and northern Italy (Figure 7). This roughly coincides with an area sometimes called Europe's "blue banana", in reference to the shape of the region and the color of the European Union flag. As such, the carbon tax causes a recentralization of the EU, and a strengthening of its non-agricultural base. Because the increased density of the core enhances its comparative advantage, it leads to a drop in agricultural output in those regions.

In contrast, agriculture expands in countries and regions of the EU periphery, such as Sweden, Finland, southern Spain, Romania, Bulgaria, and Greece. By the year 2100, these patterns get further magnified in southern Europe, where carbon taxes keep temperatures lower, thus enhancing the region's comparative advantage in agriculture. In Scandinavia, the opposite happens: lower temperatures erode its agricultural productivity. In regions bordering the EU, we see a clear decline in agricultural activity and an increase in non-agricultural activity. This shift is expected, given their proximity to the EU periphery which shifts increasingly into agriculture. Taken together, we see that carbon taxes with local rebating have rich and spatially heterogenous effects on specialization across the EU and its bordering regions.

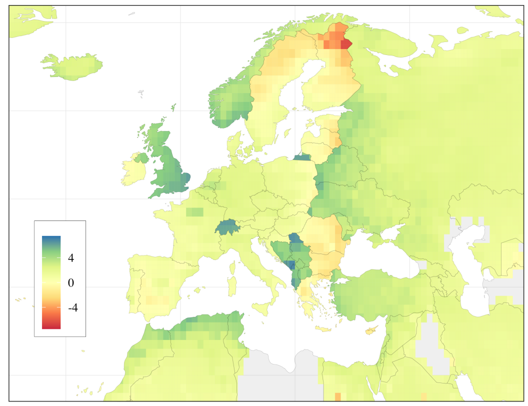
Real income, population and welfare for different tax levels. While it would be natural to expect the EU economy to shrink by less if the carbon tax is rebated locally, Figure 8 Panel (a) shows that the EU economy actually expands at impact. For a carbon tax of 40 US\$/tCO_2, EU real income increases by 0.46% in 2021 (Appendix Table D2).

Figure 7: Change in Sectoral Output Due to Carbon Taxes (Local Rebating), Europe

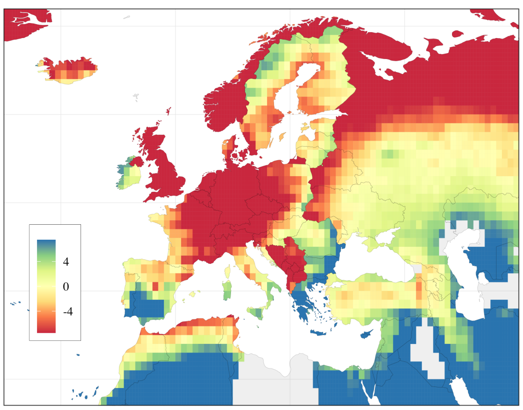
(a) % Δ Agriculture, local rebating, 2021



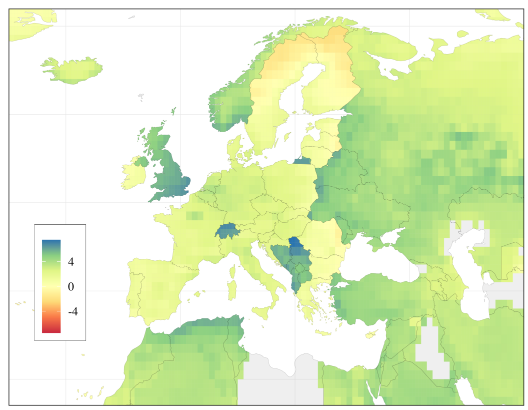
(b) % Δ Non-agriculture, local rebating, 2021



(c) % Δ Agriculture, local rebating, 2100



(d) % Δ Non-agriculture, local rebating, 2100



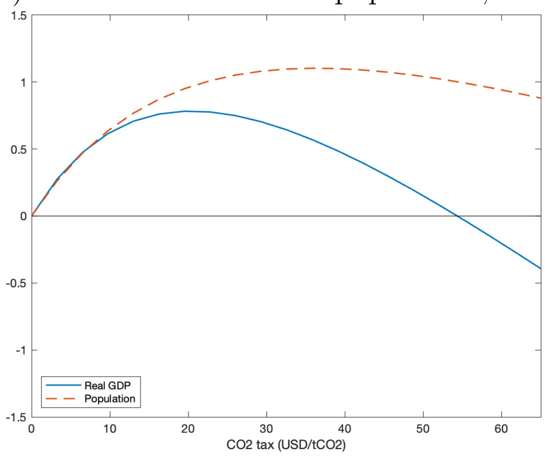
Note: Map displays the log difference (*100) in nominal sectoral output between the baseline with a carbon tax (and local rebating) and a counterfactual without a carbon tax. Panels (a) and (c) refer to agricultural nominal output, and Panels (b) and (d) to non-agricultural nominal output. Panels (a) and (b) are for 2021, whereas Panels (c) and (d) are for 2100.

The EU economy expands partly because people move to Europe. Under the baseline carbon tax, population in the EU goes up by 1.1% in 2021. Welfare in the EU falls, and this loss is increasing in the level of the carbon tax (Panel (b)). However, output per capita in non-agriculture increases, even for large carbon taxes (Appendix Figure D6). This, again, illustrates the strengthening of the EU core as a non-agricultural production hub.

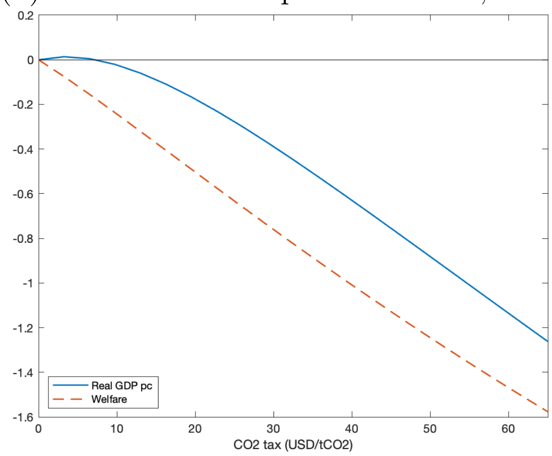
World real income per capita and welfare improve due to the EU carbon tax, with world output increasing in both sectors (Figure 9). With local rebating, the carbon tax leads to a more efficient distribution of economic activity across the globe. Although

Figure 8: Effect of Carbon Tax on EU Economy (Local Rebating), 2021

(a) % Δ real income and population, 2021



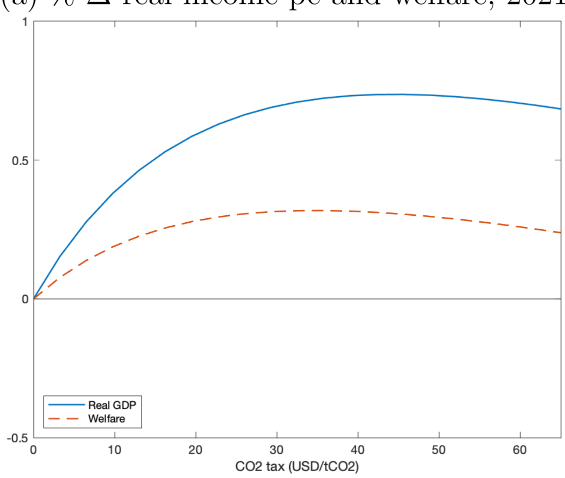
(b)% Δ real income pc and welfare, 2021



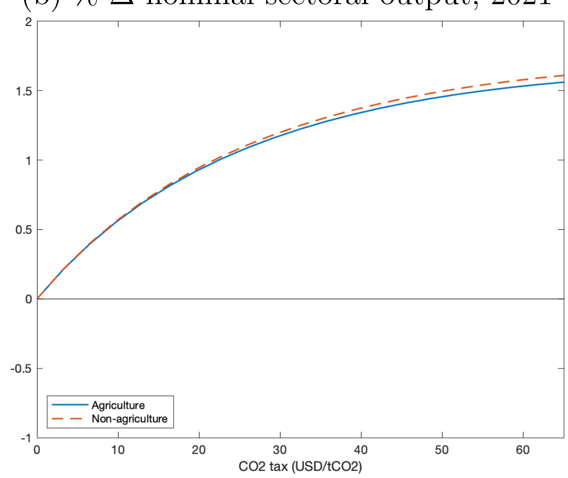
Note: For different EU variables, Figure displays the log difference (*100) in 2021 between the baseline with carbon taxes (and local rebating) and a counterfactual without carbon taxes. Panel (a) shows EU real income and population and Panel (b) shows EU real income per capita and welfare.

Figure 9: Effect of Carbon Tax on World Economy (Local Rebating), 2021

(a) % Δ real income pc and welfare, 2021



(b) % Δ nominal sectoral output, 2021

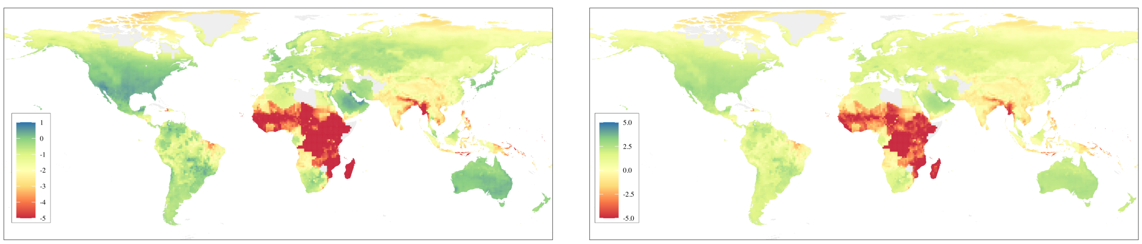


Note: For different world variables, Figure displays the log difference (*100) in 2021 between the baseline with carbon taxes (and local rebating) and a counterfactual without carbon taxes. Panel (a) shows world real income per capita and welfare, Panel (b) shows world nominal sectoral output per capita.

for the baseline tax real income per capita in 2021 declines in all major regions (-0.63% in the EU, -0.22% in the US, -0.97% in sub-Saharan Africa, and -1.13% in Asia), world real income per capita increases by 0.73%. This global gain occurs because more people move to the productive areas of the world. For a carbon tax of 40 US\$/tCO_2, population in 2021 increases in the EU, the U.S., and Japan, and drops in sub-Saharan Africa and South and East Asia. By 2100, some of the major regions, such as the U.S., gain in terms of real income per capita. For the world as a whole, in 2100 real income per capita is predicted to increase by 1.29% in response to the carbon tax. Population changes follow real income per capita changes. Figure 10 depicts this on a world map. Appendix Figure E1 shows that the global efficiency and welfare effects of the EU carbon tax are robust to changes in θ and Ω.

Figure 10: Effect of Carbon Tax on Real Income per Capita and Population across the Globe (Local Rebating)

(a) %Δ real income pc, 2100 (b) %Δ population, 2100



Note: Map displays log difference (*100) in 2100 between the baseline with carbon taxes (and local rebating) and a counterfactual without carbon taxes. Panel (a) shows real income per capita and Panel (b) shows population.

The overall gain in real income per capita and the greater weight of the EU economy point to carbon taxes and rebates correcting pre-existing inefficiencies. In the baseline without a carbon tax, there is not enough economic activity in the EU non-agricultural core and there is insufficient migration to the EU. The carbon tax with local rebating acts as a place-based policy that subsidizes the non-agricultural core and incentivizes people to move to the EU. As Europe's weight in non-agriculture increases, regions such as sub-Saharan Africa and South and East Asia increasingly revert back to agriculture. As this increases income per capita differences, there is out-migration from those regions to the EU and other developed regions across the globe. These flows improve global real income per capita and welfare. This suggests that an EU carbon tax may lead to a double win for the world: it increases global welfare and it reduces emissions and global warming. From the point of the EU, it increases the weight of its economy and it reinforces its non-agricultural core.

However, these positive effects come at the cost of greater spatial inequality. Appendix Table D2 shows larger real income per capita losses in 2100 in low-income regions, such as sub-Saharan Africa (-2.37%) and South and East Asia (-1.26%), than in high-income regions, such as the European Union (-0.44%) and the US (+0.13%). Welfare effects in these regions follow similar patterns.

Which pre-existing inefficiencies might a carbon tax with local rebating correct? The world's economic geography is shaped by agglomeration and congestion externalities, and carbon emissions constitute a global externality that affects temperature and welfare. In principle, a carbon tax might reduce the inefficiency stemming from any of these externalities. As can be seen in Appendix Table D2, the effects on global welfare are already present in 2021, when the carbon tax is first introduced. This is before any possible effect on global warming. As such, this points to the carbon tax correcting inefficiencies coming from agglomeration and congestion externalities. By 2100, the welfare effect of the carbon tax is magnified, so that in the long run its impact on global warming might also play a role in reducing certain inefficiencies.

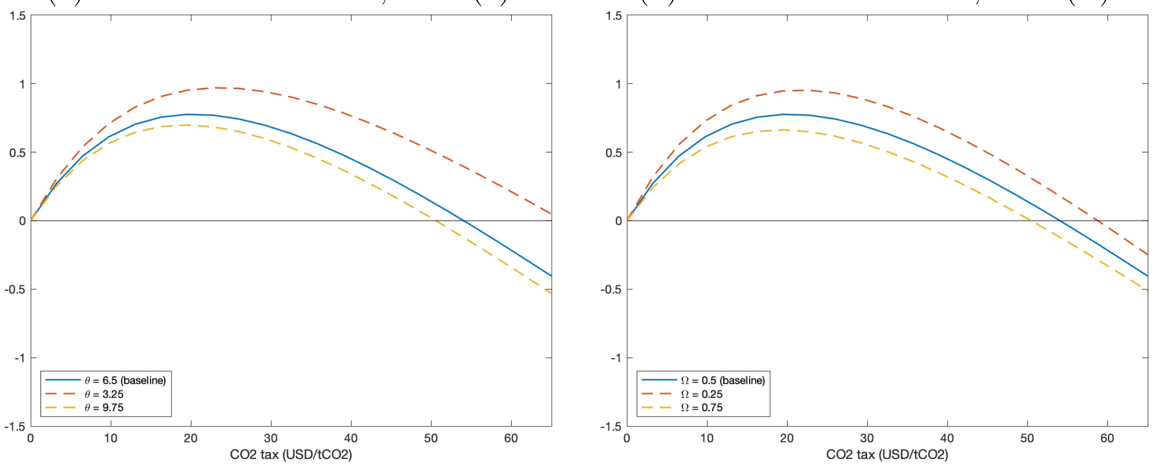
Carbon emissions. Going from no rebating to local rebating does not change EU and global emissions much. With local rebating, EU emissions drop slightly less than in a scenario with no rebating, by around 40% instead of by around 43% in 2021 (Appendix Figure D7 and Table D2). This small difference can be understood as a consequence of the EU economy expanding with local rebating. Because the tax revenues from the carbon tax are not lost, the EU attracts more population. By shifting more people into the more productive regions, emissions per unit of output produced drop. When focusing on global emissions, overall emissions drop by around 2% with or without rebating.

Effect of trade elasticity and preferences heterogeneity. Recall the argument for why a unilateral carbon tax may expand the EU economy. The higher tax burden in non-agriculture is only partly passed on to wages, so once local rebating occurs, relative income per capita in locations specialized in non-agriculture increases. This attracts migrants to the EU core, and the economy expands. As explained in Section 2.2, the size of this effect depends crucially on the trade elasticity, θ, and on the degree of preference heterogeneity, Ω.

If the trade elasticity θ is low, the increase in the relative price of non-agricultural goods due to the carbon tax has a smaller negative effect on local revenue and local income. Because of this, once we add the rebate, the overall positive effect on local income will be greater. As a result, more people will move to the EU core, and the economy of the European Union will expand by more. Hence, for low values of θ we should see a greater expansion of the EU. Figure 11 Panel (a) show the effects on

Figure 11: Effect of Different θ and Ω on EU Outcomes with Local Rebating, 2021

(a) % Δ EU real income, 2021 (θ) (b) % Δ EU real income, 2021 (Ω)



Note: Figure displays the effect of EU carbon taxes in the case of local rebating on EU real income for different values of θ (Panel (a)) and for different values of Ω (Panel (c)).

real income for values of θ that are 50% higher and 50% lower than the baseline.[15] Appendix Figure D8 Panel (a) shows a similar picture for population. Consistent with our argument, we indeed find larger positive effects on EU real income and EU population for smaller values of θ.

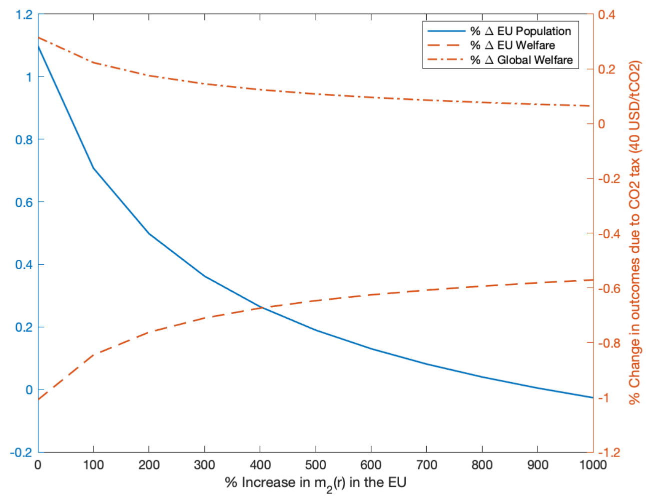
If locational preference heterogeneity Ω is low, the elasticity of migration to income differences is large. In that case, the relative increase in income in the EU core induced by the carbon tax attracts more migrants, both from within and from outside the EU. The concentration of more people in the most productive areas of the EU leads to a larger expansion of EU output. The lower the value of Ω, the greater these effects should be. Figure 11 Panel (b) plots the effects on real income for both higher (+50%) and lower (-50%) values of Ω. Appendix Figure D8 Panel (b) shows a similar picture for population. In line with our argument, the EU grows more in terms of population and real income for smaller values of Ω.

Migration barriers. The negative welfare effect within the EU in response to the carbon tax is partly the result of the migratory response that increases its population.

[15]In this exercise, we are keeping the baseline economy in 2020 unchanged. Taking the alternative parameter value for θ and without recalculating trade and migration costs, we re-invert the model using the data that come out of the baseline simulated model of 2020. As such, our economy in 2020 with the alternative parameter value will be identical to the simulated baseline economy in 2020 in terms of the spatial distribution of total population, total output and agricultural output.

To gauge the importance of this mechanism, suppose we made it harder to move to the European Union. With fewer people entering the EU, we would expect the lower labor supply and congestion to limit EU welfare losses. At the same time, with less reallocation from less productive places to the EU, we would expect global welfare gains to be lower.

Figure 12: Effect of Carbon Tax on EU for Different Migration Costs (Local Rebating), 2021



Note: Figure displays the % change in EU population, EU welfare and global welfare in 2021 between the baseline with carbon taxes (and local rebating) and a counterfactual without carbon taxes for different percentage increases in the cost of entering the EU.

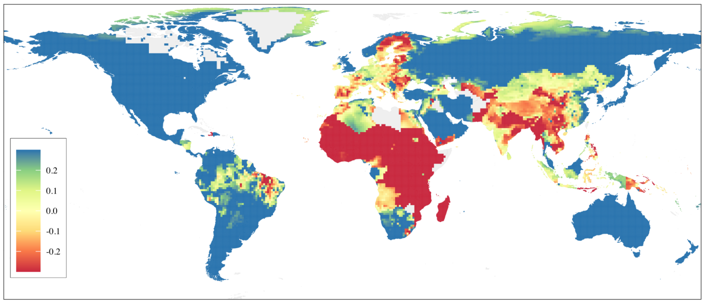
Figure 12 depicts the effect of the carbon tax for different increases in the cost of entering the EU. The horizontal axis represents the percentage increase in $m_2(r)$ for all cells r that are within the EU,[16] the left vertical axis shows the percentage change in the EU population, and the right vertical axis represents the percentage change in either global or local welfare. As expected, when migration barriers increase, fewer people enter the EU, the global welfare gains from the EU carbon tax weaken, and the local welfare losses in the EU drop.

One noticeable finding is that even when migratory barriers are raised to a level that keeps the European Union's population constant, the welfare losses in the EU do not turn into gains. If there are no welfare gains, why would lower barriers attract

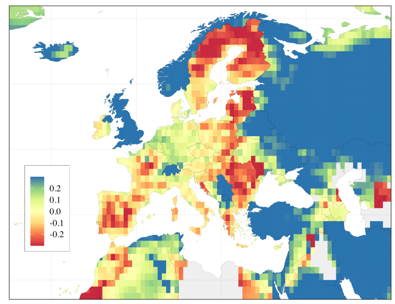
[16]Note that such increases do not affect the cost of moving within the European Union. Recall that the cost of entering a cell r is the inverse of the cost of leaving cell r, i.e., $m_2(r) = m_1(r)^{-1}$. Hence, if someone migrates between two cells r and s of the EU, the cost $m(r,s) = m_1(r)m_2(s) = m_2(r)^{-1}m_2(s)$ is invariant to a proportional increase in $m_2(r)$ and $m_2(s)$.

Figure 13: Effect of Carbon Tax with Increased Migratory Barriers in EU (Local Rebating), 2021

(a) %Δ population World, 2021



(b) %Δ population Europe, 2021



Note: Maps display log population difference (*100) in 2021 between the baseline with carbon taxes (and local rebating) and a counterfactual without carbon taxes. Migration barriers $m_2(r)$ in the EU are set so that EU population remains unchanged compared to the no carbon tax case.

migrants to the EU? There are at least two answers to this question. On the one hand, the EU carbon tax causes economic leakage that benefits developed countries and hurts the developing world. This explains why we see people move from sub-Saharan Africa and South Asia to the developed world even if Europe is closed (Figure 13, Panel (a)). These same forces push people from developing countries to the EU when migratory barriers are lowered. On the other hand, there are heterogeneous effects within the EU. Even if the EU population is constant, we see reallocation from the periphery to the core (Figure 13, Panel (b)). The same forces that make the EU core attractive to migrants from the EU periphery also make it attractive to migrants from developing countries when migratory barriers are lowered.

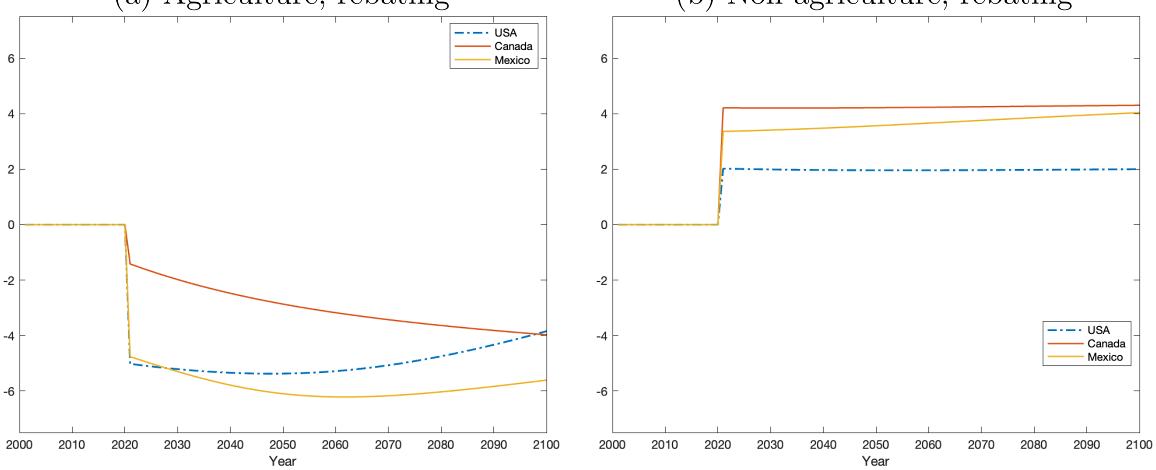
Other rebating schemes. Appendix C discusses two alternative rebating schemes: EU-wide rebating, where the EU carbon tax revenue is rebated on a per-capita basis to the whole EU population, and developing countries rebating, where the EU carbon tax is rebated on a per-capita basis to lower-income countries. Compared to local rebating, EU rebating benefits the EU periphery more and the EU core less. As a result, the expansionary impact on the EU economy is smaller. World welfare still increases, but less than under local rebating. As for developing countries rebating, it slows down out-migration from the world's lower-income regions. World welfare drops, but spatial inequality is mitigated.

5 Carbon Taxes in the United States

The impact of carbon taxes that we have uncovered using the example of the EU are not specific to that region. To illustrate this, in this section we analyze the impact of a unilateral carbon tax in the United States. The policy is exactly the same as before, with the only difference that the tax is introduced by the US, rather than by the European Union. That is, we simulate the model for 100 years, from 2000 to 2100, and introduce a carbon tax in the United States of 40US$/t$CO_2$ from 2021 onward. We consider what happens when revenues from the US carbon tax are rebated locally on a per-capita basis to the cells that paid the tax. The case of no rebating is discussed in detail in Appendix D.

Figure 14: Change in Sectoral Output due to US Carbon Tax (Local Rebating), Select Countries

(a) Agriculture, rebating (b) Non-agriculture, rebating

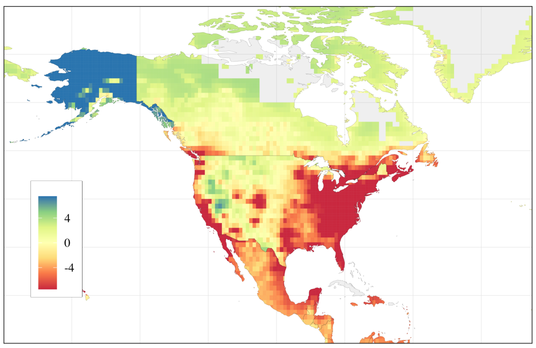


Note: Figure displays for different countries the log difference (*100) in nominal sectoral output between the baseline with carbon taxes (and local rebating) and a counterfactual without a carbon tax. Panel (a) refers to agricultural nominal output, and Panel (b) to non-agricultural nominal output.

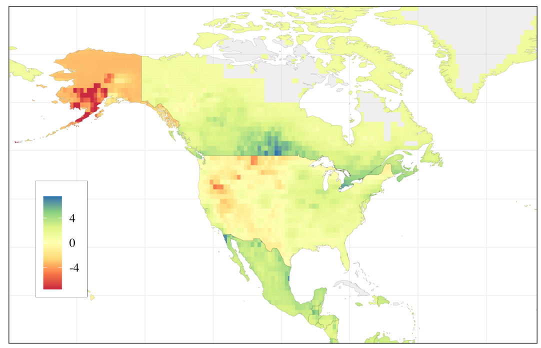
As in the case of the EU, the higher tax incidence on non-agricultural goods is not fully passed on to lower wages, so that once we account for local rebating, regions specialized in non-agriculture experience relative gains in income. This attracts migrants to those areas, causing an overall expansion of non-agricultural output (Figure 14). This strengthens the non-agricultural regions of the country, in particular the industrial Midwest, the Northeast, parts of the South and coastal California. Within these regions, especially the urban centers, such as Chicago, San Francisco, New York and St. Louis gain. Agriculture expands in the non-coastal western part of the country, parts of the Midwest and Alaska. Because the carbon tax slows down warming, by 2100 Alaska's advantage in agriculture erodes, whereas the West's and the Southwest's advantage strengthens (Figure 15).

Figure 15: Change in Sectoral Output due to US Carbon Tax (Local Rebating), USA

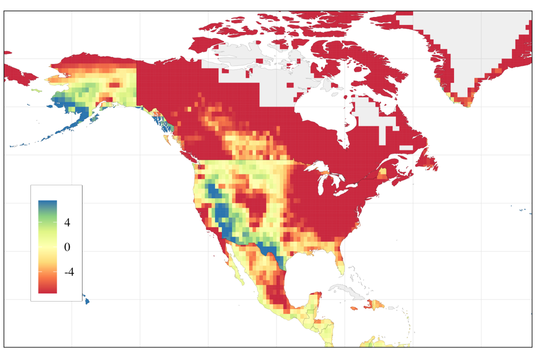
(a) % Δ Agriculture, local rebating, 2021



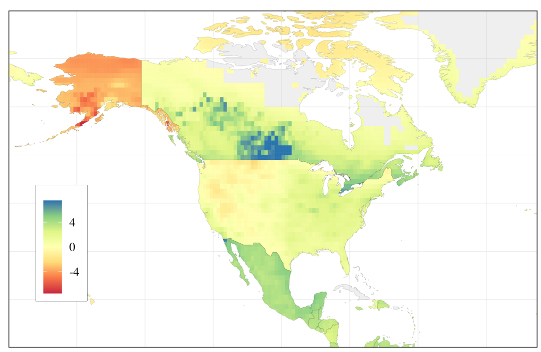
(b) % Δ Non-agriculture, local rebating, 2021



(c) % Δ Agriculture, local rebating, 2100



(d) % Δ Non-agriculture, local rebating, 2100



Note: Map displays the log difference (*100) in nominal sectoral output between the baseline with a carbon tax (and local rebating) and a counterfactual without a carbon tax. Panels (a) and (c) refer to agricultural nominal output, and Panels (b) and (d) to non-agricultural nominal output. Panels (a) and (b) are for 2021, whereas Panels (c) and (d) are for 2100.

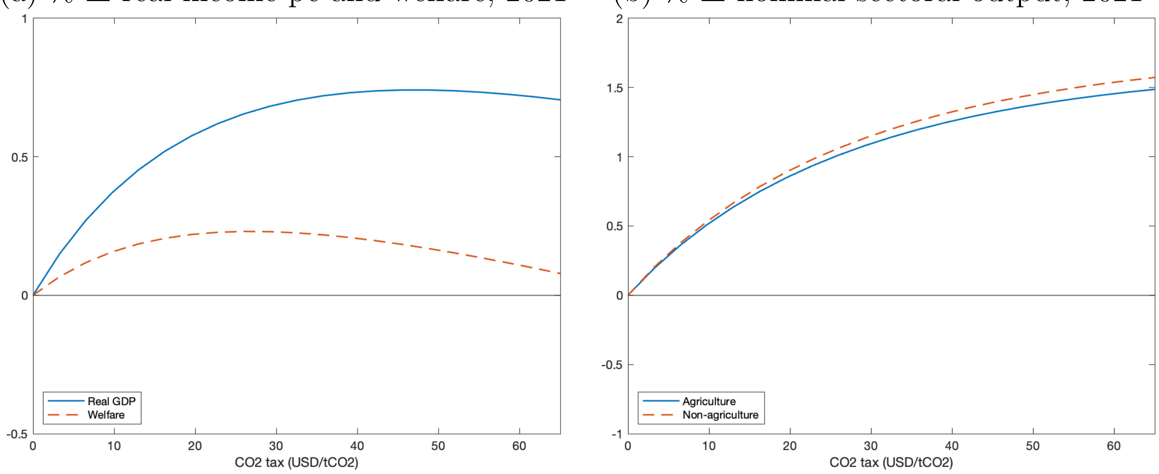
The mechanism at work is the same as in the case of an EU carbon tax: there is added concentration of population and economic activity in the regions with a strongest comparative advantage in non-agriculture. While in the European Union this shows up as a reallocation from the continent's periphery to its core, in the US this shows up as a reallocation towards the densest areas of the Northeast, the Midwest and the West

Coast. In other words, once we do the appropriate mapping in terms of the geography of specialization between the US and the EU, the effects of a unilateral carbon tax are very similar in both places.

Because of the migratory response, population and real income in the US expands (Appendix Figure F5). For a carbon tax of 40 US$/t$CO_2$, US population increases by 1.24% and its real income goes up by 0.59% in 2021. Part of the US expansion is due to in-migration from the rest of the world and part is due to internal migration, from less dense, less productive regions to more dense, more productive regions. Per capita real income in the US declines by 0.64% and welfare drops by 1.14% in 2021 (Appendix Table F2).

Figure 16: Effect of US Carbon Tax on World Economy (Local Rebating), 2021

(a) % Δ real income pc and welfare, 2021 (b) % Δ nominal sectoral output, 2021

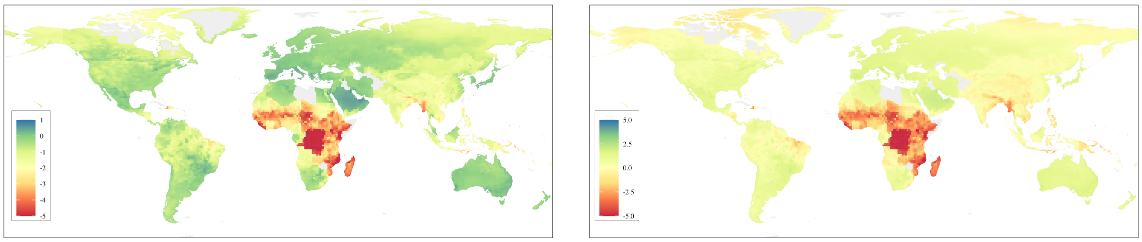


Note: Figure displays the 2021 log difference (*100) in world real income per capita and welfare (Panel (a)) and nominal sectoral output per capita (Panel (b)) between the baseline with carbon taxes (and local rebating) and a counterfactual without carbon taxes.

The global reallocation of population and economic activity generates global welfare gains (Figure 16). As in the case of the EU carbon tax, welfare in 2021 declines in all major regions of the world (EU -0.47%, sub-Saharan Africa -2.37%, Japan -0.85%), but the migration of people from less productive to more productive regions improves overall welfare (+0.21%). By 2100, the global welfare gains grow to 0.49%. At the end of the 21st century, population in sub-Saharan Africa is predicted to be 2.58% lower, whereas in the EU the population is predicted to grow by 1.5%, compared to a world without a US carbon tax (Figure 17 and Appendix Table F2). As we already saw in the EU,

Figure 17: Effect of US Carbon Tax on Real Income per Capita and Population across Globe (Local Rebating)

(a) %Δ real income pc, 2100 (b) %Δ population, 2100



Note: Map displays log difference (*100) in 2100 between the baseline with carbon taxes (and local rebating) and a counterfactual without carbon taxes. Panel (a) shows real income per capita and Panel (b) shows population.

the introduction of a carbon tax in the US corrects a pre-existing spatial inefficiency. In the absence of a carbon tax, there is not enough economic activity in the world's most productive places. As emphasized before, these global gains already materialize upon impact in 2021, before additional benefits in the form of reduced emissions.

One concern with local rebating is that it might increase global emissions. By benefiting the more energy-intensive non-agricultural sector, local rebating reduces US emissions by less than in the absence of rebating. However, in terms of magnitude, the effect is small: in 2021, emissions in the US drop by 40.5% when tax revenues are locally rebated, only slightly less than the 43.66% decline when there is no rebating. Moreover, there is a compensating effect: by keeping more non-agriculture in the US, there is less leakage to other parts of the world (Appendix Figure F6). With local rebating, emissions in the EU increase by 10.03%, whereas in the absence of rebating EU emissions grow by 11.58% (Appendix Table F2). Globally, the change in emissions between rebating schemes is a wash. With local rebating, global emissions decline by 2.06% in 2021, essentially the same as the 2.04% decline in the case of no rebating (Appendix Figure F7).

Overall, the introduction of a unilateral carbon tax in the US has very similar effects to the introduction of a unilateral carbon tax in the EU. This is not surprising: the US and the EU are similar, in terms of both their economic size and their comparative advantage in non-agriculture. A carbon tax with local rebating redistributes income to the regions specialized in the energy-intensive non-agricultural sector. In both the US and the EU, this tax acts as a place-based policy that benefits high-productivity non-agricultural locations. As this generates a migratory response, there are global efficiency and welfare gains due to pre-existing distortions in the spatial distribution of economic activity.

6 Conclusion

Unilateral carbon policy has an effect on the spatial distribution of economic activity and its efficiency. Understanding this impact can help design better carbon policy and minimize, and even revert, the short-run negative local effects of the policy. This paper uses a dynamic spatial integrated assessment model (S-IAM) to evaluate the economic effects of a unilateral carbon tax implemented by either the European Union or the United States. With local rebating, we find that such a carbon tax would expand the size of the economy that introduces the tax and improve global welfare. Local rebating of the tax acts as a place-based policy that subsidizes non-agricultural regions and incentivizes people to move to either the EU or the US. With a greater share of the world population residing in the developed world, global efficiency and global welfare improve. Alternative rebating schemes lead to different results. In particular, rebating the revenues of the EU carbon tax to developing countries improves the lot of lower-income countries. This slows down migration to the EU, leading to a less efficient spatial distribution of population and economic activity. As a result, global welfare declines. Our analysis underscores the importance of taking into account the spatial effects of carbon taxes. Because the initial spatial equilibrium need not be efficient, carbon taxes have the potential of improving efficiency, though this depends on how tax revenues are rebated, as well as on their size.

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A Appendix: Proof of Lemma

Proof. The proof consists of three parts. Part 1 shows how the introduction of a small carbon tax in region r affects firm revenues, wages, and land rents in the region. Part 2 proves that a small carbon tax with local rebating leads to an increase in the region's income. Part 3 shows that the region's population expands.

Part 1

The introduction of a carbon tax affects the marginal cost of firms. This impacts their revenues, and hence the wages and land rents they pay. We start by writing down an expression of how local firm revenues change with a change in marginal cost. We then show how a change in firm revenues affects local wages and land rents. The goal is to get expressions for how local wages and land rents change with the introduction of a carbon tax.

The revenue of firms producing varieties of good i in location r equals total spending on these varieties in the entire world. Following Conte et al. (2021), this implies that the revenue of sector i in period t and location r, denoted by $\xi_{it}(r)$, can be written as $\xi_{it}(r) = \Gamma_i \varrho_{it}(r) \int_S P_{it}(s)^\theta y(s)$, where

$$\begin{aligned}
\Gamma_i &= \chi_i \kappa_i \\
\varrho_{it}(r) &= \tau_{it}(r)^\theta g_i \left(T_t(r)\right)^\theta \tilde{e}_t^{-\sigma_i\theta} w_t(r)^{-(\alpha_i+\gamma_i+\mu_i)\theta} R_t(r)^{(\alpha_i-\zeta_i)\theta} \\
\kappa_i &= \bar{p}^{-\theta} \gamma_i^{\gamma_i\theta} \mu_i^{\mu_i\theta} \sigma_i^{\sigma_i\theta} \left(\gamma_i+\mu_i\right)^{\alpha_i\theta} \left(1-\gamma_i-\mu_i-\sigma_i\right)^{(1-\alpha_i-\gamma_i-\mu_i-\sigma_i)\theta} \\
\tilde{e}_t &= e_t(1+\Upsilon_t) \\
\zeta_i &= 1-\gamma_i-\mu_i-\sigma_i.
\end{aligned}$$

Given that region r is small, a change in its marginal cost does not affect the price index in any location, so $\mathrm{d}P_{it}(s) = 0 \ \forall \ s$. Income in other locations is also unaffected, whereas any change in the own region's income does not affect local firm revenues because the own region is small. Totally differentiating the above expression then gives

$$\begin{aligned}
\mathrm{d}\xi_{it}(r) = &-\theta\sigma_i\Gamma_i\tilde{e}_t^{-\sigma_i\theta-1}\tau_{it}(r)^\theta g_i\left(T_t(r)\right)^\theta w_t(r)^{-(\alpha_i+\gamma_i+\mu_i)\theta} R_t(r)^{(\alpha_i-\zeta_i)\theta} \int_S P_{it}(s)^\theta y(s)\varsigma(s,r)^{-\theta}\mathrm{d}s \ \mathrm{d}\tilde{e}_t \\
&-(\alpha+\gamma_i+\mu_i)\theta\Gamma_i\tilde{e}_t^{-\sigma_i\theta}\tau_{it}(r)^\theta g_i\left(T_t(r)\right)^\theta w_t(r)^{-(\alpha_i+\gamma_i+\mu_i)\theta-1} R_t(r)^{(\alpha_i-\zeta_i)\theta} \int_S P_{it}(s)^\theta y(s)\varsigma(s,r)^{-\theta}\mathrm{d}s \ \mathrm{d}w_t \\
&-(\zeta_i-\alpha_i)\theta\Gamma_i\tilde{e}_t^{-\sigma_i\theta}\tau_{it}(r)^\theta g_i\left(T_t(r)\right)^\theta w_t(r)^{-(\alpha_i+\gamma_i+\mu_i)\theta} R_t(r)^{(\alpha_i-\zeta_i)\theta-1} \int_S P_{it}(s)^\theta y(s)\varsigma(s,r)^{-\theta}\mathrm{d}s \ \mathrm{d}R_t \\
= &-\theta\sigma_i\xi_{it}(r)\frac{\mathrm{d}\tilde{e}_t}{\tilde{e}_t} - (\alpha_i+\gamma_i+\mu_i)\theta\xi_{it}(r)\frac{\mathrm{d}w_t}{w_t} - (\zeta_i-\alpha_i)\theta\xi_{it}(r)\frac{\mathrm{d}R_t}{R_t}.
\end{aligned}$$

Because location r is small, it does not affect the world energy price. Hence, $\mathrm{d}\tilde{e}_t = \tilde{e}_t d\Upsilon$, so that

$$\mathrm{d}\xi_{it}(r) = -\theta\sigma_i\xi_{it}(r)\mathrm{d}\Upsilon - \theta(\alpha_i+\gamma_i+\mu_i)\xi_{it}(r)\frac{\mathrm{d}w_t}{w_t} - \theta(\zeta_i-\alpha_i)\xi_{it}(r)\frac{\mathrm{d}R_t}{R_t}. \tag{15}$$

The introduction of a carbon tax, $\mathrm{d}\Upsilon$, has a direct effect on the marginal cost of firms by raising the cost of energy. However, because the higher marginal cost lowers firm revenues, it will also indirectly impact wages and land rents. As such, the changes in revenues, wages and land rents induced by the carbon tax are jointly determined. In what follows, we write down expressions for the changes in wages and land rents that make this explicit. Total spending on land is a fixed share of firm revenues, $R_t(r)H(r) = \sum_i \zeta_A\xi_{it}(r)$. Totally differentiating land rents yields:

$$\begin{aligned}\mathrm{d}\left(R_t(r)H(r)\right) &= \zeta_A\mathrm{d}\xi_{At}(r) + \zeta_M\mathrm{d}\xi_{Mt}(r)\\ &= -\theta\sum_i \zeta_i\xi_{it}(r)\left[\sigma_i\mathrm{d}\Upsilon + (\alpha_i+\gamma_i+\mu_i)\frac{\mathrm{d}w_t(r)}{w_t(r)} + (\zeta_i-\alpha_i)\frac{\mathrm{d}R_t(r)}{R_t(r)}\right].\end{aligned}$$

Rewriting this expression gives

$$\mathrm{d}R_t = \frac{-\theta\mathrm{d}\Upsilon\sum_i\sigma_i\zeta_i\xi_{it}(r) - \frac{\theta\mathrm{d}w_t(r)}{w_t(r)}\sum_i(\alpha_i+\gamma_i+\mu_i)\zeta_i\xi_{it}(r)}{\left[H(r) + \theta\sum_i\zeta_i\xi_{it}(r)\frac{(\zeta_i-\alpha_i)}{R_t(r)}\right]}. \tag{16}$$

By analogy, we can derive an expression for the change in wages:

$$\mathrm{d}w_t(r) = \frac{-\theta\mathrm{d}\Upsilon\sum_i\left((\mu_i+\gamma_i)\sigma_i\xi_{it}(r)\right) - \frac{\theta\mathrm{d}R_t(r)}{R_t(r)}\left((\mu_i+\gamma_i)(\zeta_i-\alpha_i)\xi_{it}(r)\right)}{\left[\bar{L}_t(r) + \theta\sum_i\left((\mu_i+\gamma_i)\xi_{it}(r)\frac{(\alpha_i+\gamma_i+\mu_i)}{w_t(r)}\right)\right]}. \tag{17}$$

Equations (16) and (17) form a system of two linear equations: $\mathrm{d}R_t(r) = -A - B\mathrm{d}w_t(r)$ and $\mathrm{d}w_t(r) = -C - D\mathrm{d}R_t(r)$. Solving for these equations yields

$$\mathrm{d}R_t(r) = \Lambda_r\mathrm{d}\Upsilon \tag{18}$$

$$\mathrm{d}w_t(r) = \Lambda_w\mathrm{d}\Upsilon. \tag{19}$$

where $\Lambda_r = \frac{\Phi_r}{\Psi_r}$, $\Lambda_w = \frac{\Phi_w}{\Psi_w}$,

$$\Phi_r = \theta \left\{ \sum_i (\alpha_i + \gamma_i + \mu_i)\zeta_i \xi_{it}(r) \right\} \left\{ \sum_i (\mu_i + \gamma_i)\sigma_i \xi_{it}(r) \right\}$$
$$- \left\{ \sum_i \zeta_i \sigma_i \xi_{it}(r) \right\} \left\{ \bar{L}_t(r) w_t(r) + \theta \sum_i (\mu_i + \gamma_i)(\alpha_i + \gamma_i + \mu_i)\xi_{it}(r) \right\}$$
$$\Psi_r = \left\{ H(r) + \frac{\theta}{R_t(r)} \sum_i \left(\zeta_i \xi_{it}(r)(\zeta_i - \alpha_i) \right) \right\} \left\{ \frac{\bar{L}_t(r) w_t(r)}{\theta} + \sum_i (\mu_i + \gamma_i)(\alpha_i + \gamma_i + \mu_i)\xi_{it}(r) \right\}$$
$$- \frac{\theta}{R_t(r)} \left\{ \sum_i (\alpha_i + \gamma_i + \mu_i)\zeta_i \xi_{it}(r) \right\} \left\{ \sum_i (\gamma_i + \mu_i)(\zeta_i - \alpha_i)\xi_{it}(r) \right\}.$$

and analogous expressions for Φ_w and Ψ_w. Equations (18) and (19) clarify how a change in carbon taxes affects local land rents and wages.

Part 2

To see how a carbon tax affects local income, we need to include the tax rebate. Tax revenue earned, and rebated, by the government is $A_t(r) = \Upsilon e_t E_t(r)$. Totally differentiating this expression gives $\mathrm{d}A_t(r) = e_t E_t(r)\mathrm{d}\Upsilon + \Upsilon \mathrm{d}(e_t E_t(r))$. Given that we are assessing the effect of $\mathrm{d}\Upsilon$ starting at $\Upsilon = 0$, the relevant tax rebate is:

$$\mathrm{d}A_t(r)|_{\Upsilon=0} = e_t E_t(r)\mathrm{d}\Upsilon|_{\Upsilon=0} = \sum_i \sigma_i \xi_{it}(r)\mathrm{d}\Upsilon. \tag{20}$$

Total local income is the sum of wage income, land rents, profits, and rebate income:

$$y_t(r)\bar{L}(r) = w_t(r)\bar{L}(r) + R_t(r)H(r) + \Pi_t + \frac{A_t(r)}{\bar{L}(r)},$$

where in equilibrium $\Pi_t = 0$. We now analyze the change in total local income following the introduction of a carbon tax, $\mathrm{d}\Upsilon$:

$$\begin{aligned} \bar{L}(r)\frac{\mathrm{d}y_t(r)}{\mathrm{d}\Upsilon}|_{\Upsilon=0} =& \frac{\mathrm{d}A_t(r)}{\mathrm{d}\Upsilon}|_{\Upsilon=0} + \bar{L}(r)\frac{\mathrm{d}w_t(r)}{\mathrm{d}\Upsilon} + H(r)\frac{\mathrm{d}R_t(r)}{\mathrm{d}\Upsilon} \\ =& \sum_i \sigma_i \xi_{it}(r) + \bar{L}(r)\Lambda_w + H(r)\Lambda_r. \end{aligned} \tag{21}$$

Note that for now we are analyzing the impact on local income *before* the possibility of any migration. Hence, we are keeping $\bar{L}(r)$ constant. If $\alpha = 0$, the change in total local income (21) is proportional to the reduction in total revenues of local firms. Starting with (15), the change in total revenues of local firms can be written as

$$\sum_i \mathrm{d}\xi_{it}(r) = -\theta \sum_i \left(\sigma_i \xi_{it}(r) \mathrm{d}\Upsilon + (\alpha_i + \gamma_i + \mu_i) \xi_{it}(r) \frac{\mathrm{d}w_t}{w_t} + (\zeta_i - \alpha_i) \xi_{it}(r) \frac{\mathrm{d}R_t}{R_t} \right).$$

Using the first order conditions, $(\gamma_i + \mu_i)\xi_{it}(r) = w_t(r)\bar{L}_{it}(r)$ and $\zeta_i \xi_{it}(r) = R_t(r)H_i(r)$, as well as (18), (19), and the assumption $\alpha = 0$, the above expression simplifies to

$$\sum_i \mathrm{d}\xi_{it}(r) = -\theta \sum_i \left(\sigma_i \xi_{it}(r) + \Lambda_w \bar{L}_t(r) + \Lambda_r H(r) \right), \tag{22}$$

which is proportional to (21). We know that total revenues of local firms must decrease upon the introduction of a carbon tax. Suppose total revenues were to go up instead. Then the total revenues going to land and labor would increase.[17] For a given endowment of labor and land, this implies that local wages and local land rents must go up. Because the local energy price has also increased (due to the carbon tax), the marginal cost of firms must have increased. However, this would lower the quantity demanded, and therefore lower total revenue if the demand is elastic. Thus, this would be inconsistent with total revenue increasing. We can therefore conclude that total revenues of local firms must decrease, so that (22) is negative:

$$-\theta \sum_i \left(\sigma_i \xi_{it}(r) + \Lambda_w \bar{L}_t(r) + \Lambda_r H(r) \right) < 0. \tag{23}$$

This implies that the change in total income (21) is positive, and therefore the change in per capita local income is positive too:

$$\frac{\mathrm{d}y_t(r)}{\mathrm{d}\Upsilon}|_{\Upsilon=0} > 0. \tag{24}$$

This proves that local per capita income increases following the introduction of a small carbon tax.

Part 3

Consider the proportion of population living in region r:

$$\bar{L}_t(r) = \frac{u_t(r)^{1/\Omega} m_2(r)^{-1/\Omega}}{\int_S u_t(s)^{1/\Omega} m_2(s)^{-1/\Omega} \mathrm{d}s} \bar{L}$$

where $u_t(r) = a_t(r) \frac{y_t(r)}{\prod_{i=1}^{I} P_{it}(r)^{\chi_i}}$ and $P_{it}(r) = \left[\int_0^1 p_{it}^{\omega}(r)^{\frac{\rho}{\rho-1}} \,\mathrm{d}\omega \right]^{\frac{\rho-1}{\rho}}$. As such, when $y_t(r)$

[17] In a model with one sector, this is straightforward. In a model with two sectors that have different levels of energy intensity, but the same trade elasticity θ, production would shift toward the least energy-intensive sector. This would increase the share of total revenues going to land and labor, and hence magnify the total revenue going to land and labor.

increases, there is an increase in the proportion of $\bar{L}$ living in region r since:

$$\begin{aligned}
\mathrm{d}\bar{L}_t(r) &= \frac{1}{\Omega}\frac{u_t(r)^{(1-\Omega)/\Omega}m_2(r)^{-1/\Omega}}{\int_S u_t(s)^{1/\Omega}m_2(s)^{-1/\Omega}\mathrm{d}s}\bar{L}\mathrm{d}u_t(r) \\
&= \frac{1}{\Omega}\bar{L}_t(r)\frac{\mathrm{d}u_t(r)}{u_t(r)} \\
&= \frac{1}{\Omega}\bar{L}_t(r)\frac{\mathrm{d}y_t(r)}{y_t(r)} > 0 \quad \text{for } \mathrm{d}y_t(r) > 0, \Omega > 0. \qquad (25)
\end{aligned}$$

■

Online Appendix

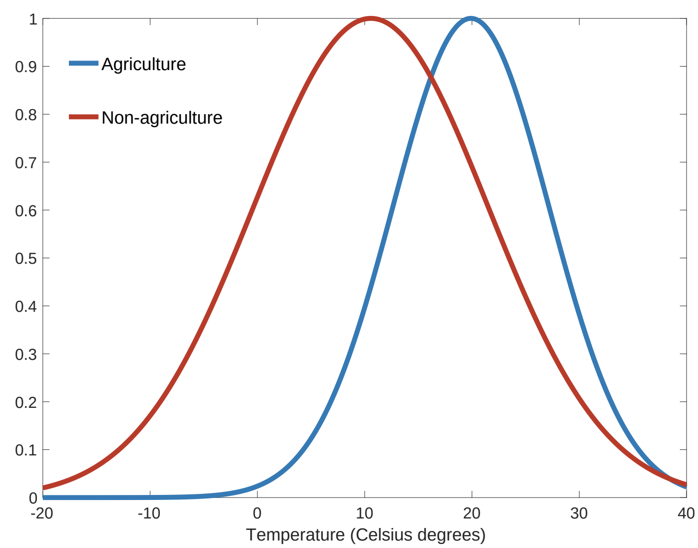
B Appendix: Calibration

Table B1: Parameter Values

Parameter	Target/Comment
1. Preferences	
$\beta = 0.96$	Annual discount factor
$\rho = 0.75$	Elasticity of substitution of 4[1]
$\lambda = 0.32$	Relation between amenities and population[1]
$\Omega = 0.5$	Elasticity of migration flows with respect to income[1]
$\psi = 1.8$	Subjective well-being parameter[1]
$\chi_A = 0.051$	Data on agricultural and total output
$\chi_M = 0.949$	Data on agricultural and total output
2. Technology	
$\alpha_A = 0$	No agglomeration externality in agriculture
$\alpha_M = 0.01$	Agglomeration externality in non-agriculture[1]
$\theta = 6.5$	Trade elasticity[1]
$\mu_A = \mu_M = 0.6$	Labor share in agriculture and non-agriculture[2]
$\gamma_A = 0.001$	Growth rate of agricultural productivity[3]
$\gamma_M = 0.0002$	Growth rate of non-agricultural productivity[3]
$\sigma_A = 0.04$	Energy share in agriculture (Schnepf, 2004; Australian Bureau of Statistics, 2021)
$\sigma_M = 0.07$	Energy share in non-agriculture (Grubb et al., 2018; King et al., 2015)
$\delta = 0.993$	Technology diffusion[1]
$\aleph = 0.004$	Spatial decay of diffusion[4]
$\phi = 0.25$	Energy supply elasticity[2]
3. Temperature and carbon cycle	
$g_A^{opt} = 19.9°\text{C}$	Optimal temperature in agriculture[2]
$g_A^{var} = 7.28°\text{C}$	0.1% of world agricultural production at locations below discount factor 0.01
$g_M^{opt} = 10.5°\text{C}$	Relationship between non-agricultural productivity and temperature
$g_M^{var} = 11.0°\text{C}$	Relationship between non-agricultural productivity and temperature
$\varepsilon_1 = 0.9975$	Decay of carbon stock[2]
$\varepsilon_2 = 0.29$	1200 GTC increase in global carbon stock by 2100
$\nu = 0.0031$	3.7°C increase in global temperature by 2100

[1]Desmet et al. (2018), [2]Desmet and Rossi-Hansberg (2015), [3]Duarte and Restuccia (2010), [4]Comin et al. (2012). Note that α_M in the current paper is equal to α_M divided by θ in Desmet et al. (2018).

Figure B1: Temperature Discount in Agriculture and Non-Agriculture

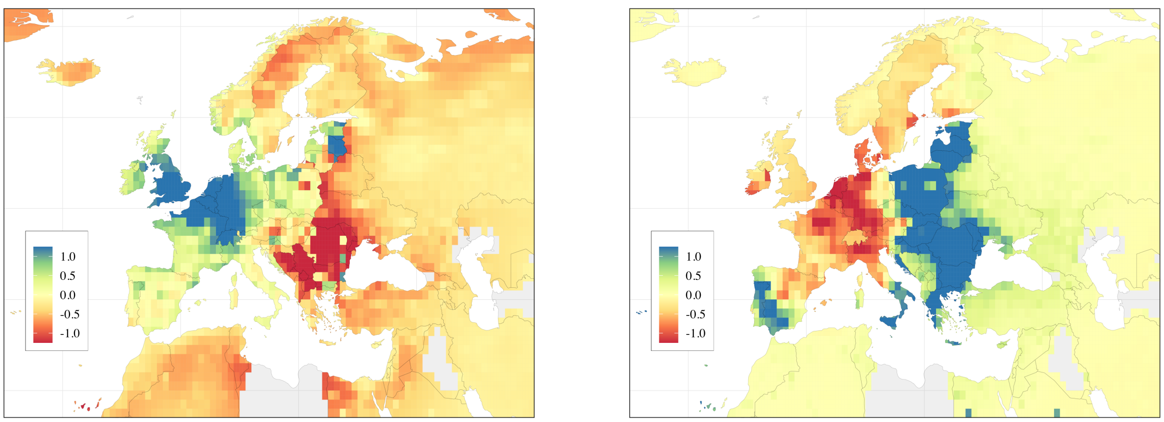


C Appendix: Alternative Rebating Schemes

In this section we consider two additional rebating schemes: EU rebating, where the EU carbon tax revenue is rebated on a per-capita basis to the whole EU population, and developing countries rebating, where the EU carbon tax is rebated on a per-capita basis to lower-income countries, defined as countries with an income per capita below that of the poorest EU country.

Figure C1: Change in Sectoral Output Due to Carbon Taxes: EU Rebating vs Local Rebating

(a) % Δ agr., EU – local rebating, 2021 (b) % Δ non-agric., EU – local rebating, 2021

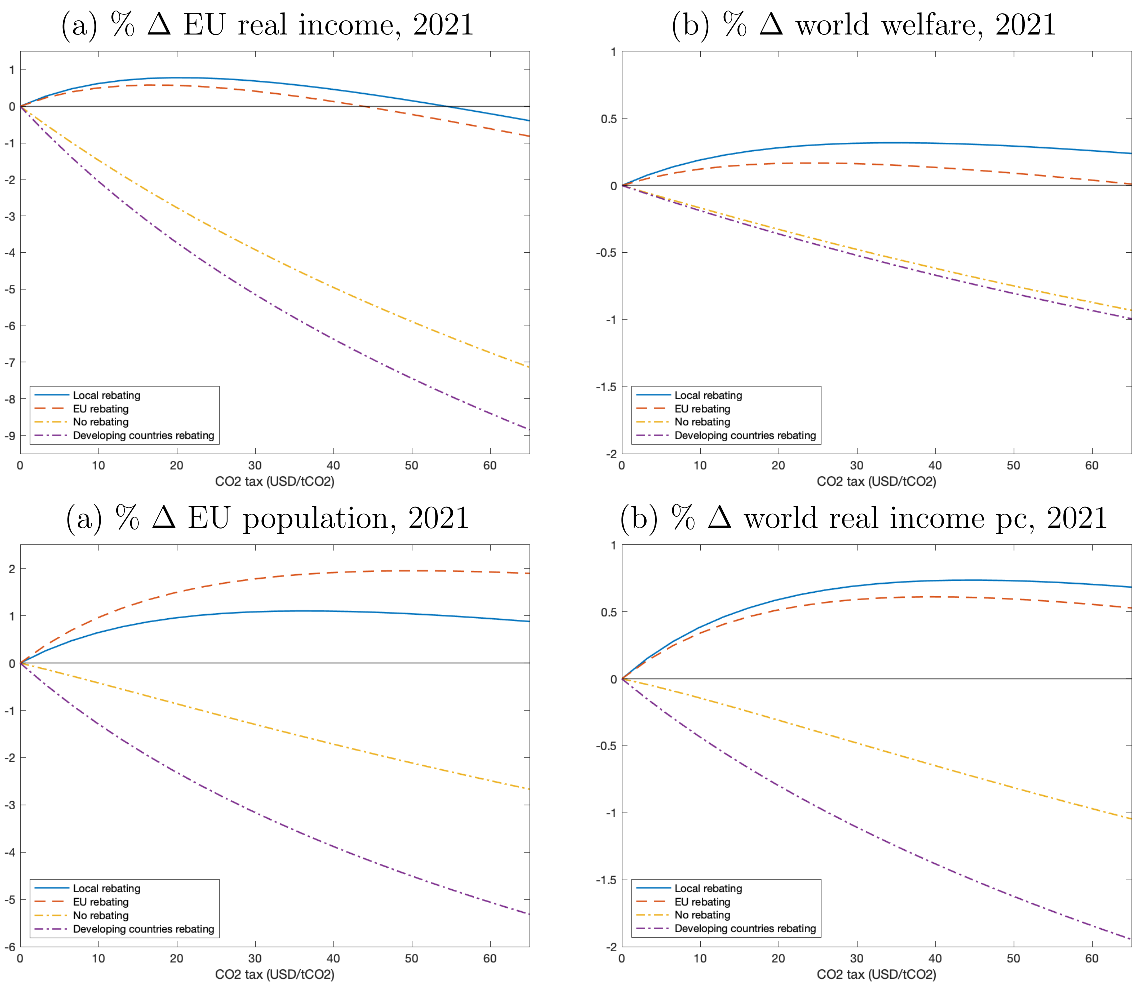


Note: Maps display log difference (*100) in nominal agricultural and non-agricultural output in 2021 between the case with a carbon tax and EU rebating and the case with a carbon tax and no rebating.

Compared to local rebating, EU rebating benefits the EU periphery more and the EU core less. Because the richer non-agricultural core contributes more on a per-capita basis to carbon tax revenues, EU rebating amounts to a transfer from the EU core to the EU periphery. As a result, the positive impact of the carbon tax on the non-agricultural EU core is smaller (Figure C1). Real income in the EU expands less than under local rebating (Figure C2 Panel (a)). World welfare and real income per capita continue to increase, but less so than under local rebating (Panels (b) and (d)).

Developing countries rebating, instead, benefits lower-income countries. From the point of view of the EU, the revenue from the carbon tax is lost. It is therefore not surprising that the EU shrinks, both in terms of real income and population (Figure C2, panels (a) and (b)). In fact, the drop in income and population in the EU is greater than when the proceeds of the tax are thrown away. The reason is simple: developing

Figure C2: Effect of Different Rebating Schemes on EU and World Economy, 2021



Note: Figure displays the effect of EU carbon taxes under different rebating schemes (no rebating, local rebating, EU rebating, and developing countries rebating) in 2021 on EU real income (Panel a), world welfare (Panel b), EU population (Panel c), and world real income per capita (Panel d).

countries rebating keeps more people in low-income regions (Figure C3 Panel (a)). For the baseline carbon tax of 40 US\$/tCO_2, population in sub-Saharan Africa increases by 0.66% in 2021, compared to a drop of 2.14% under no rebating and a drop of 2.47% under local rebating. Slowing down out-migration from Africa and South East Asia also has global efficiency effects. For the baseline carbon tax, developing countries rebating lowers world real income per capita in 2021 by 1.38%, compared to an increase of 0.73% in the case of local rebating (Table C1). Spatial inequality is mitigated though: in 2100 real income per capita is 2.08% lower in the EU and 2.22% higher in sub-Saharan Africa.

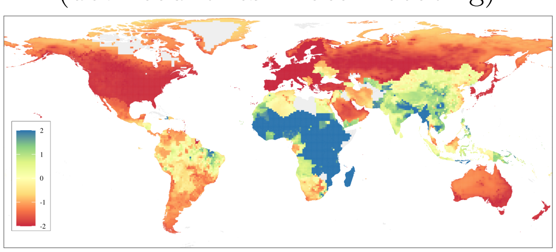
Table C1: Effect of Carbon Tax on Different Regions of the World (EU and Developing Countries Rebating)

	World		EU		US		Japan		SSA		Asia	
	2021	2100	2021	2100	2021	2100	2021	2100	2021	2100	2021	2100
Panel A: EU rebating												
%Δ Real GDP	0.61	1.15	0.13	0.9	1.69	2.68	1.49	2.46	-3.48	-6.28	-1.52	-1.79
%Δ Real GDP pc	0.61	1.15	-1.75	-1.43	-0.19	0.16	-0.28	0.09	-0.95	-2.36	-1.12	-1.25
%Δ Welfare	0.13	0.51	-2.51	-2.6	-0.8	-0.62	-0.85	-0.67	-2.38	-3.24	-1.53	-1.82
%Δ Population	0	0	1.92	2.37	1.88	2.51	1.78	2.37	-2.55	-4.01	-0.4	-0.54
%Δ Agricultural Output	1.22	2.51	-2.85	-1.8	2.25	5.16	2.75	6.64	1.37	10.62	2.24	4.05
%Δ Non-agric. Output	1.26	2.54	1.42	2.14	1.33	2.8	0.45	2.21	-0.56	-0.07	-0.68	0.36
%Δ Emissions	-2.16	-2.69	-40.62	-38.86	10.59	14.67	9.63	14.01	8.66	11.5	8.75	12.51
Panel B: Developing countries rebating												
%Δ Real GDP	-1.38	-1.78	-6.37	-6.33	0.53	1.03	0.39	0.85	1.45	3.41	1.25	2.35
%Δ Real GDP pc	-1.38	-1.78	-2.59	-2.08	0.55	1.3	0.48	1.24	0.79	2.22	0.81	1.68
%Δ Welfare	-0.67	-0.68	-1.32	-0.71	0.54	1.41	0.5	1.36	0.8	2.11	0.74	1.8
%Δ Population	0	0	-3.88	-4.35	-0.01	-0.26	-0.09	-0.39	0.66	1.17	0.44	0.66
%Δ Agricultural Output	-1.47	-1.23	-1.05	2.43	-0.33	-1.08	0.15	-0.11	-1.85	5.98	-1.23	-0.29
%Δ Non-agric. Output	-1.45	-1.19	-6.29	-5.78	-0.02	0.83	-0.19	0.71	0.89	2.75	0.75	2.25
%Δ Emissions	-2.57	-3.27	-44.15	-42.22	10.93	15.16	10.75	15.02	11.74	17.37	11.54	16.38

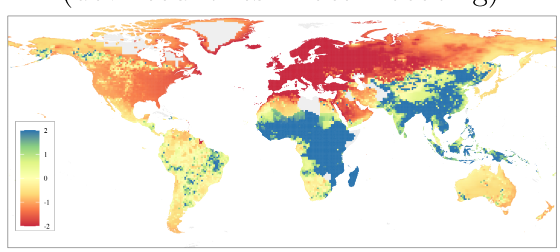
Note: For different variables and regions of the world, Table displays log difference (*100) between the baseline with a carbon tax and a counterfactual without a carbon tax. Panel (a) shows results for a carbon tax with EU rebating (where the EU carbon tax revenue is rebated on a per-capita basis to the EU population), and Panel (b) shows results for a carbon tax with developing countries rebating (where the EU carbon tax revenue is rebated on a per-capita basis to developing countries). SSA refers to Sub-saharan Africa, and S. & E. Asia refers to South and East Asia, which includes Bangladesh, Brunei, China, Indonesia, India, Cambodia, Laos, Sri Lanka, Myanmar, Malaysia, Philippines, Thailand, and Vietnam.

Figure C3: Effect of Carbon Tax across the Globe (Developing countries vs Local Rebating)

(a) %Δ population, 2021 (dev. countries – local rebating)



(b) %Δ non-agric., 2021 (dev. countries – local rebating)

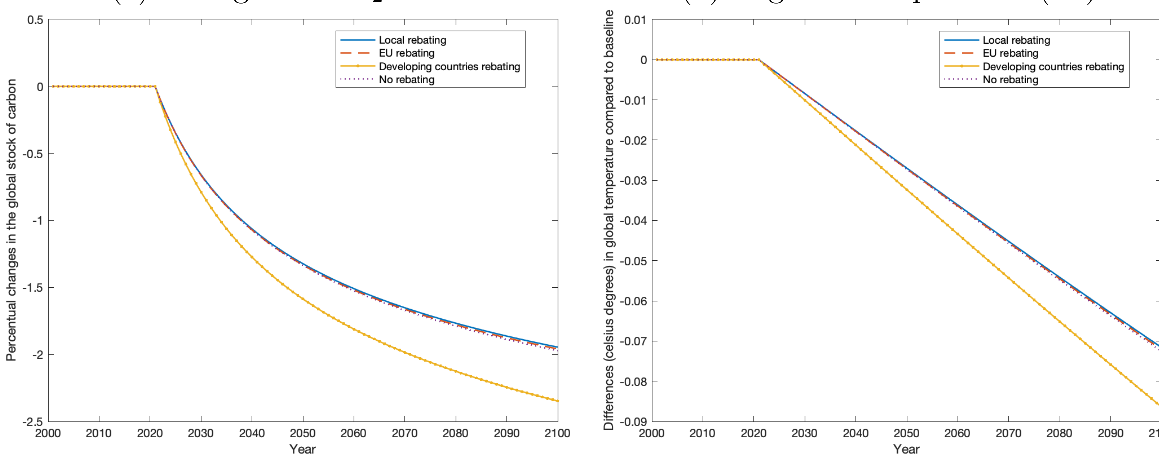


Note: Maps display the log difference (*100) in population and nominal non-agricultural output between a carbon tax with developing countries rebating and a carbon tax with local rebating.

When looking at the impact on the carbon stock and temperature, we notice that developing countries rebating reduces emissions and lowers temperature more than other rebating schemes (Figure C4). This is due to developing countries rebating lowering world production more than other rebating arrangements. The effects are still small in

Figure C4: Effect of Different Rebating Schemes on Global CO_2 Stock and Temperature

(a) % Δ global CO_2 stock (b) Δ global temperature (°C)



Panel (a) displays change in global CO_2 stock under different rebating schemes, and Panel (b) displays change in global temperature (°C) under different rebating schemes.

magnitude: by 2100 the stock of carbon declines by 2-2.5% compared to a world without carbon taxes, and global temperatures go down by almost 0.1°C. Recall, of course, that we are considering a carbon tax implemented only by the EU. To have larger effects on global temperatures, either the carbon tax would have to be substantially larger, or the carbon tax would have to be implemented by more countries.[18]

[18]See Cruz and Rossi-Hansberg (2022) for a related finding on the small effect of the unilateral pledges in the Paris Agreement.

D Appendix: Additional Figures and Tables

D.1 Additional Tables

Table D1: Effect of Carbon Tax on Different Regions of the World (No Rebating)

	World		EU		US		Japan		SSA		S. & E. Asia	
	2021	2100	2021	2100	2021	2100	2021	2100	2021	2100	2021	2100
%Δ Real GDP	-0.65	-0.63	-4.96	-4.29	2.02	3.14	1.88	2.93	-3.1	-5.84	-1.34	-1.55
%Δ Real GDP pc	-0.65	-0.63	-3.3	-3.12	-0.2	0.17	-0.27	0.09	-0.98	-2.36	-1.19	-1.35
%Δ Welfare	-0.62	-0.52	-2.75	-2.79	-0.93	-0.77	-0.96	-0.81	-2.5	-3.39	-1.71	-2.02
%Δ Population	0	0	-1.72	-1.2	2.22	2.97	2.15	2.84	-2.14	-3.56	-0.15	-0.2
%Δ Agricultural Output	-0.07	0.74	-0.86	2.86	-0.08	0.49	-0.08	1.87	-0.22	8.63	0.59	1.94
%Δ Non-agric. Output	0.74	1.81	-3.44	-2.04	2.75	4.54	2.41	3.97	0.17	0.46	0.62	1.82
%Δ Emissions	-2.16	-2.72	-43.42	-41.27	12.11	16.75	11.75	16.11	9.29	12.22	9.81	13.73

Note: For different variables and regions of the world, Table displays log difference (*100) between the baseline with a carbon tax and no rebating and a counterfactual without a carbon tax. SSA refers to Sub-saharan Africa, and S. & E. Asia refers to South and East Asia, which includes Bangladesh, Brunei, China, Indonesia, India, Cambodia, Laos, Sri Lanka, Myanmar, Malaysia, Philippines, Thailand, and Vietnam.

Table D2: Effect of Carbon Tax on Different Regions of the World (Local Rebating)

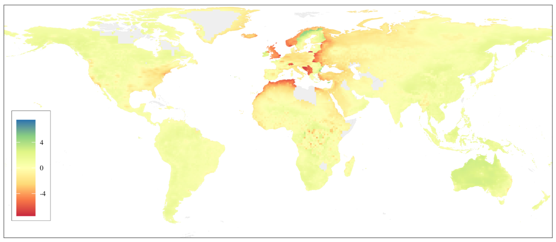
	World		EU		US		Japan		SSA		Asia	
	2021	2100	2021	2100	2021	2100	2021	2100	2021	2100	2021	2100
%Δ Real GDP	0.73	1.29	0.46	1.19	1.71	2.71	1.52	2.5	-3.42	-6.19	-1.46	-1.72
%Δ Real GDP pc	0.73	1.29	-0.63	-0.44	-0.22	0.13	-0.3	0.06	-0.97	-2.37	-1.13	-1.26
%Δ Welfare	0.32	0.81	-1.01	-1.02	-0.84	-0.66	-0.89	-0.71	-2.41	-3.27	-1.56	-1.86
%Δ Population	0	0	1.1	1.63	1.93	2.58	1.83	2.44	-2.47	-3.91	-0.33	-0.46
%Δ Agricultural Output	1.34	2.63	-3.07	-2	2.39	5.31	2.9	6.76	1.5	10.66	2.36	4.14
%Δ Non-agric. Output	1.38	2.65	1.79	2.4	1.34	2.83	0.46	2.26	-0.5	-0.01	-0.64	0.42
%Δ Emissions	-2.14	-2.68	-40.45	-38.74	10.53	14.62	9.58	13.99	8.65	11.49	8.73	12.5

Note: For different variables and regions of the world, Table displays log difference (*100) between the baseline with a carbon tax and local rebating and a counterfactual without a carbon tax. SSA refers to Sub-saharan Africa, and S. & E. Asia refers to South and East Asia, which includes Bangladesh, Brunei, China, Indonesia, India, Cambodia, Laos, Sri Lanka, Myanmar, Malaysia, Philippines, Thailand, and Vietnam.

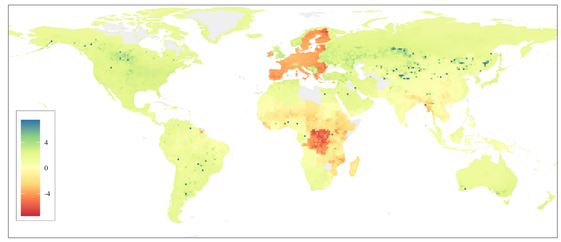
D.2 Additional Figures

Figure D1: Effect of Carbon Tax on Sectoral Ouput (No Rebating), 2021

(a) Agricultural output, no rebating, 2021



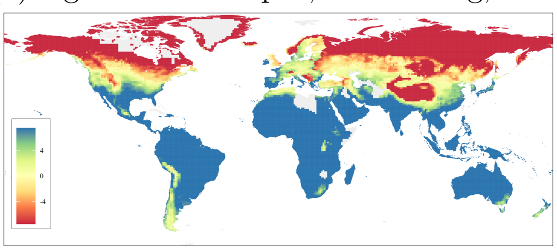
(b) Non-agricultural output, no rebating, 2021



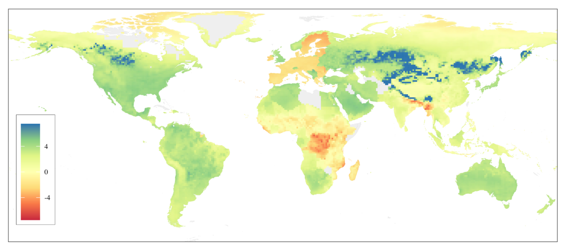
Note: Maps display log differences in nominal sectoral output in agriculture (Panel a) and non-agriculture (Panel b) in 2021 between the case with a carbon tax (and no rebating) and the case without a carbon tax.

Figure D2: Effect of Carbon Tax on Sectoral Ouput (No Rebating), 2100

(a) Agricultural output, no rebating, 2100



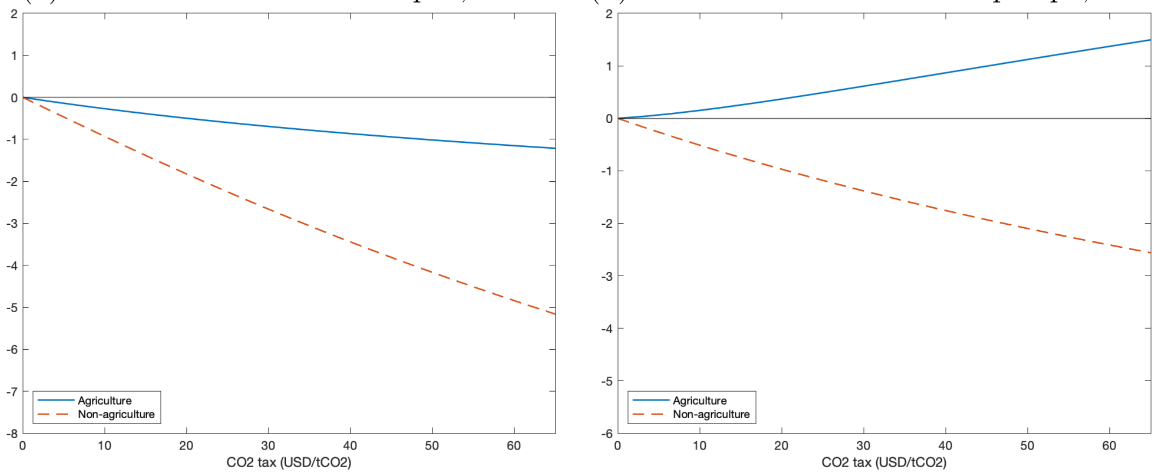
(b) Non-agricultural output, no rebating, 2100



Note: Maps display log differences in nominal sectoral output in agriculture (Panel a) and non-agriculture (Panel b) in 2100 between the case with a carbon tax (and no rebating) and the case without a carbon tax.

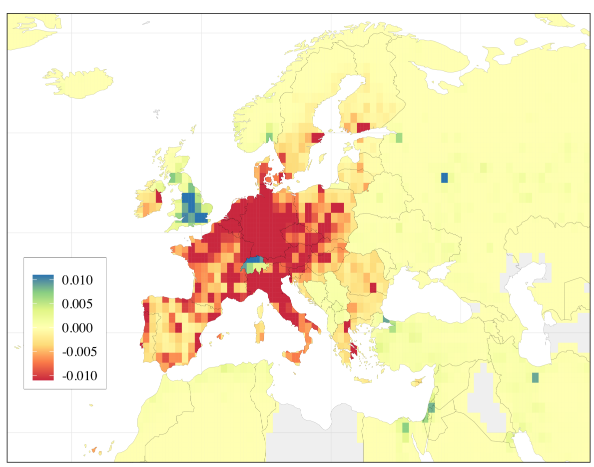
Figure D3: Effect of Carbon Tax on EU Economy (No Rebating), 2021

(a)% Δ nominal sectoral output, 2021 (b) % Δ nominal sectoral output pc, 2021



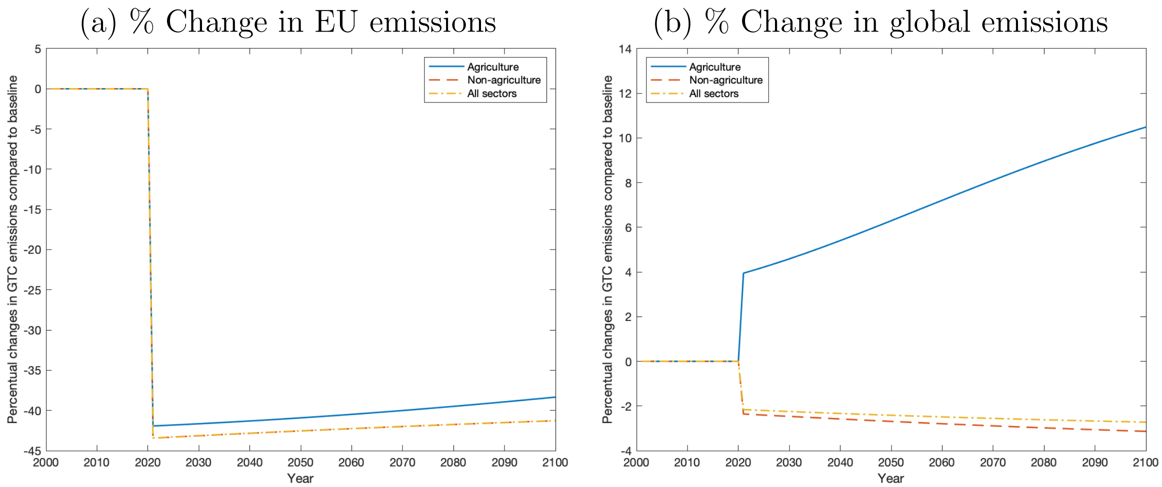
Note: For different EU variables, Figure displays the log difference (*100) in 2021 between the baseline with carbon taxes (and no rebating) and a counterfactual without carbon taxes. Panel (a) shows EU nominal sectoral output, and Panel (b) shows EU nominal sectoral output per capita.

Figure D4: Change in Emissions in the EU Due to Carbon Tax (No Rebating), 2021



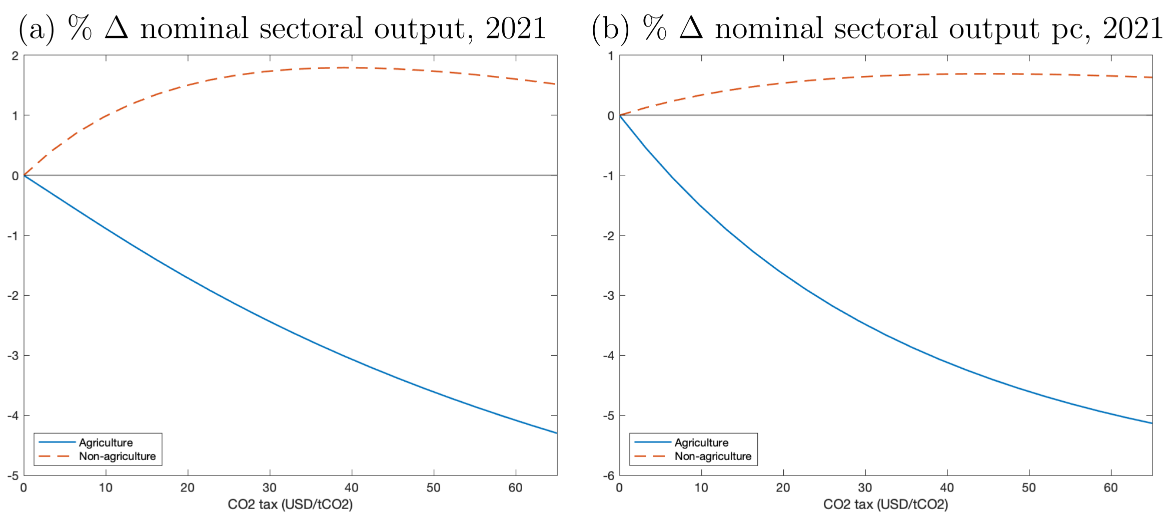
Note: Maps display differences in emissions levels (tCO_2) between the case with a carbon tax (and no rebating) and the case without a carbon tax.

Figure D5: Effect of Carbon Tax on Global and EU Emissions (No Rebating)



Note: Figure displays log difference (*100) in emissions between the baseline with carbon taxes (and no rebating) and a counterfactual without carbon taxes. Panel (a) shows EU emissions and Panel (b) shows global emissions.

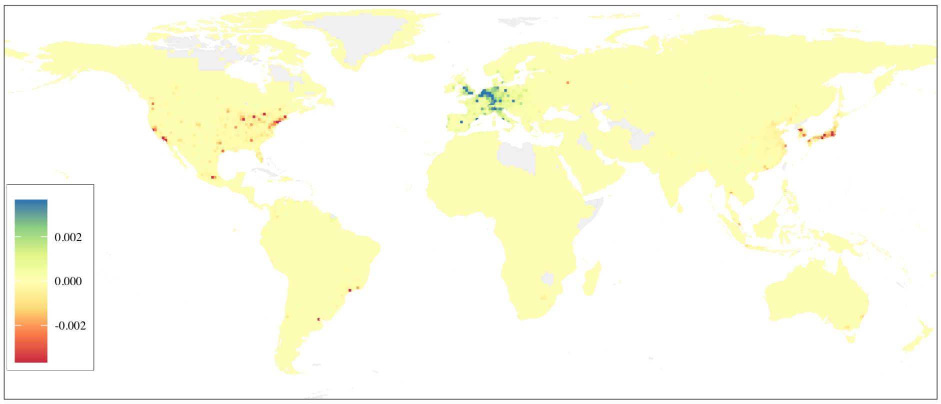
Figure D6: Effect of Carbon Tax on EU Economy (Local Rebating), 2021



Note: For different EU variables, Figure displays the log difference (*100) in 2021 between the baseline with carbon taxes (and local rebating) and a counterfactual without carbon taxes. Panel (a) shows EU nominal sectoral output and Panel (b) shows EU nominal sectoral output per capita.

Figure D7: Effect of Carbon Tax on Emissions around the World (Local vs No Rebating)

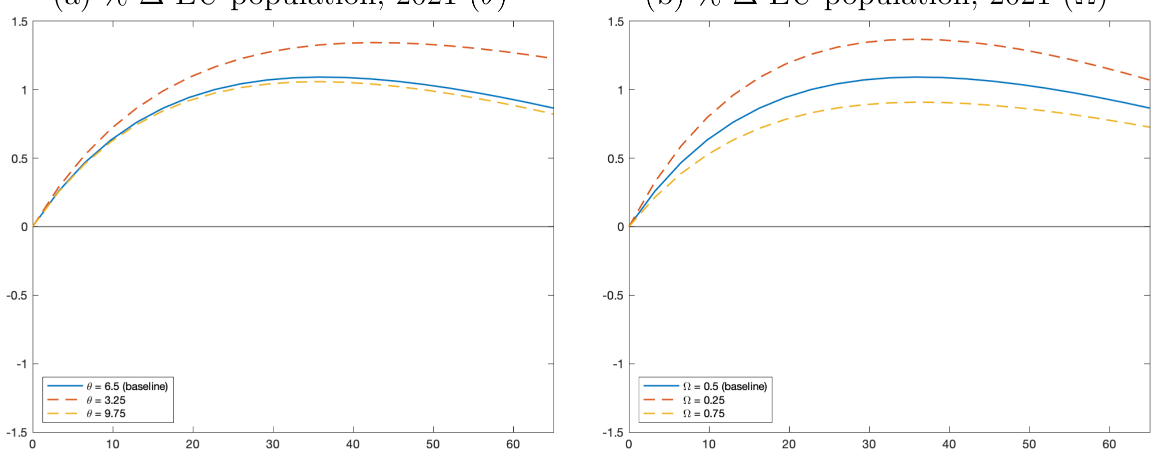
Δ emissions (local - no rebating), 2021



Note: Maps display differences in emission levels (in tCO_2) between the case with a carbon tax (and local rebating) and the case with a carbon tax (and no rebating).

Figure D8: Effect of Different θ and Ω on EU Outcomes with Local Rebating, 2021

(a) % Δ EU population, 2021 (θ) (b) % Δ EU population, 2021 (Ω)

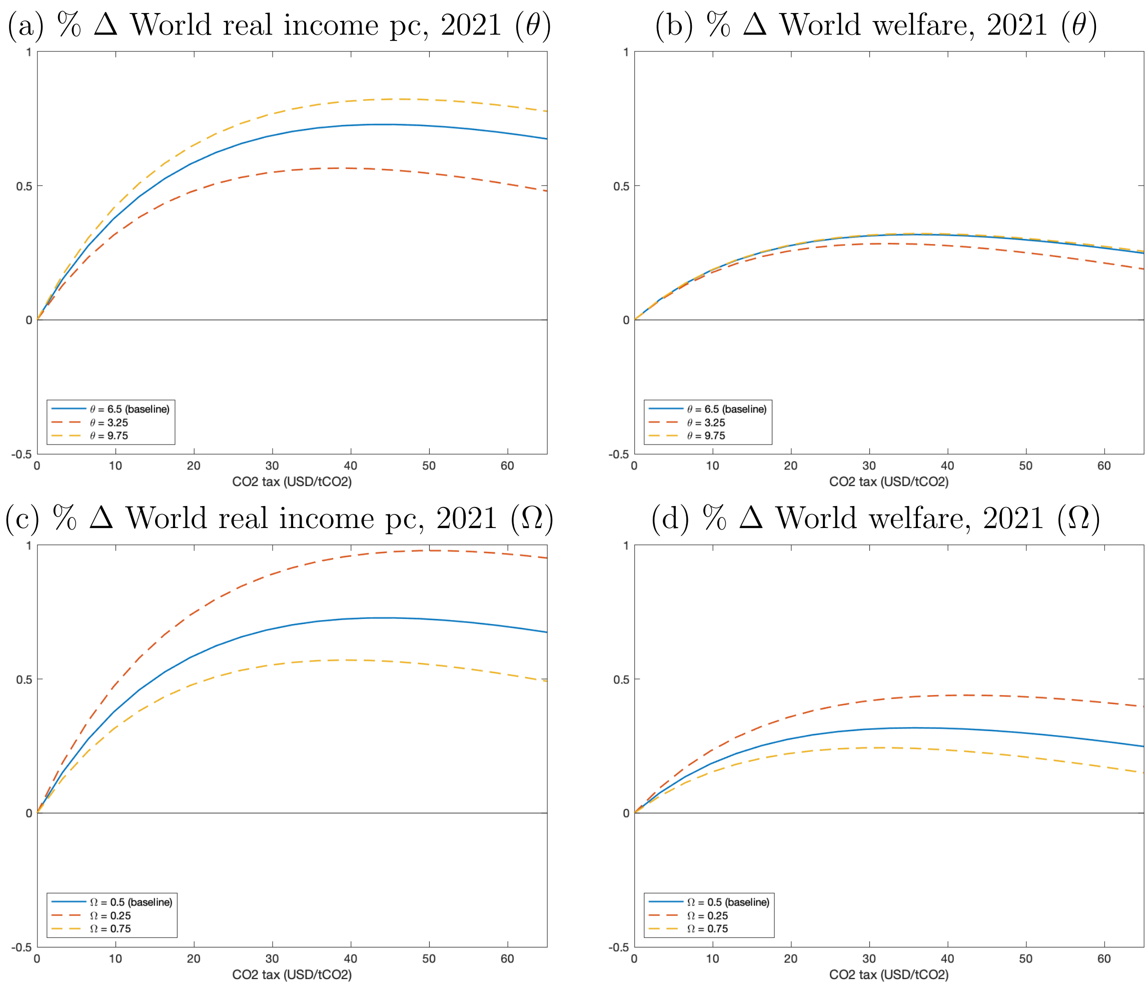


Note: Figure displays the effect of EU carbon taxes in the case of local rebating on EU population for different values of θ (Panel a) and for different values of Ω (Panel b).

E Robustness

In this subsection we show that the positive effect of an EU carbon tax on global efficiency and global welfare is robust to changes in the trade elasticity (θ) and the degree of locational preference heterogeneity (Ω). Figure E1 shows these results for both higher (+50%) and lower (-50%) values of θ and Ω. For any of these values, an EU carbon tax of 40 US\$/tCO_2 induces improvements in both global real income per capita and global welfare. This, once again, reflects the EU carbon tax generating a more efficient distribution of economic activity across the globe.

Figure E1: Effect of Different θ and Ω on World Outcomes with Local Rebating, 2021



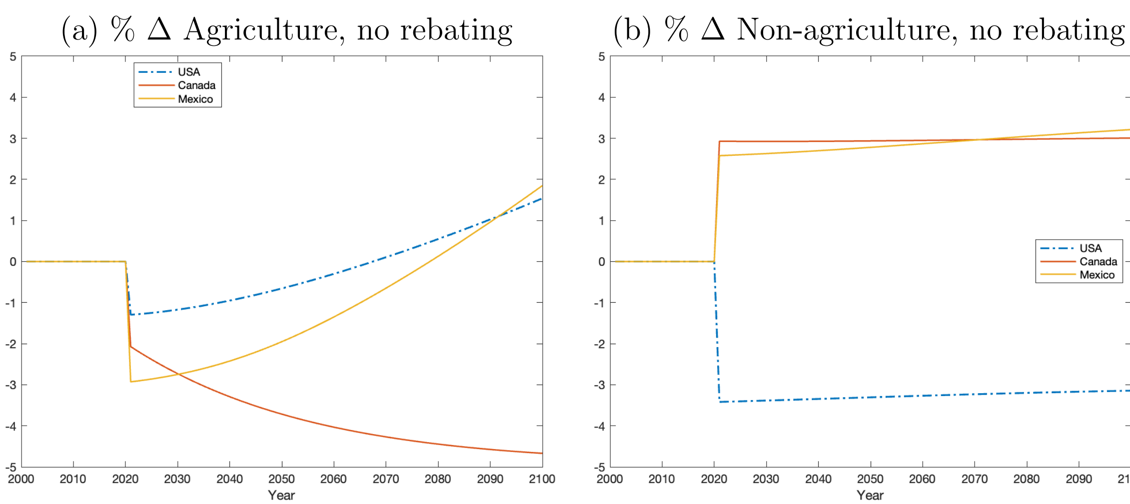
Note: Figure displays the effect of EU carbon taxes in the case of local rebating on world's real income per capita and welfare for different values of θ (Panels a and b) and for different values of Ω (Panels c and d).

F Appendix: Additional Analysis for the US

F.1 No Rebating

We first consider the case where the tax revenues from the US carbon tax are lost. In the absence of rebating, Figure F1 shows that a carbon tax shrinks the US economy, and more so in agriculture than in non-agriculture, because of the differential tax incidence across sectors. This shifting comparative advantage of the US in favor of agriculture generates a positive shock to non-agriculture in the border countries, Mexico and Canada.

Figure F1: Change in Sectoral Output Due to Carbon Tax in US (No Rebating), Select Countries

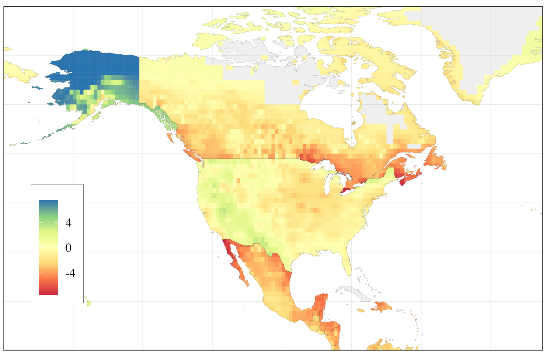


Note: Figure displays for different countries the log difference (*100) in nominal sectoral output between the baseline with carbon taxes (and no rebating) and a counterfactual without a carbon tax. Formally, for country C and sector i, it measures the difference in $100 * \log\left(\sum_{r\in\bar{C}} w_t(r)\bar{L}_{it}(r)\right)$ (which is a fixed share of nominal output) with and without carbon taxes. Panel (a) refers to agricultural nominal output, and Panel (b) to non-agricultural nominal output.

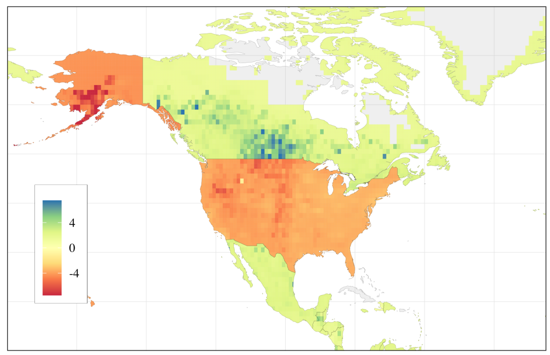
When displaying the changes on a map of North America, Figure F2 shows that when the carbon tax is first introduced, agriculture declines more in the industrial Midwest and the Northeast of the US, as well as in coastal California. In contrast, regions that have a smaller presence in non-agriculture, such as Alaska and the Mountain states, see a stronger shift into agriculture. This is particularly striking in the case of Alaska, where the expansion is reinforced by Canada's shifting comparative advantage towards non-agriculture. By 2100, the benign effect of the carbon tax on global warming is beneficial to agriculture in the southern and western regions of the US, while it hurts Alaska's position. Canada and Mexico, and especially the regions close to the US border, see an expansion of non-agricultural activity.

Figure F2: Change in Sectoral Output Due to US Carbon Tax (No Rebating), North America

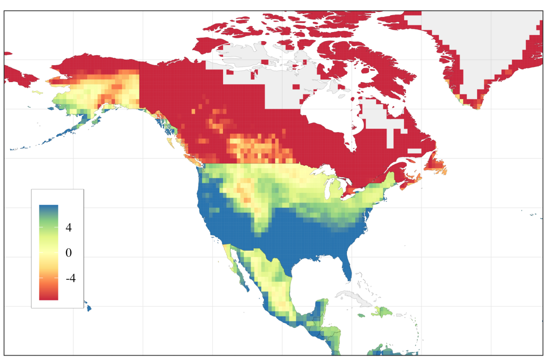
(a) % Δ Agriculture, no rebating, 2021



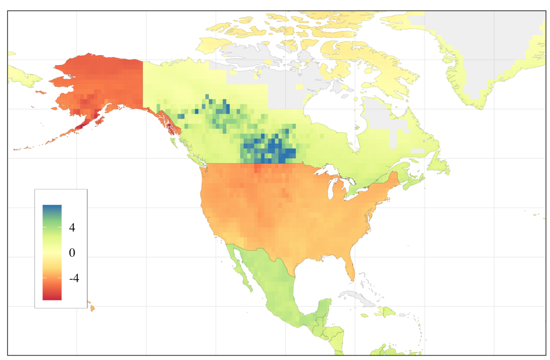
(b) % Δ Non-agriculture, no rebating, 2021



(c) % Δ Agriculture, no rebating, 2100



(d) % Δ Non-agriculture, no rebating, 2100



Note: Map displays for different countries the log difference in nominal sectoral output between the baseline with a carbon tax (and no rebating) and a counterfactual without a carbon tax. Panels (a) and (c) refer to agricultural nominal output, and Panels (b) and (d) to non-agricultural nominal output. Panels (a) and (b) are for 2021, whereas Panels (c) and (d) are for 2100.

The world map in Figure F4 shows that sub-Saharan Africa and parts of South and East Asia lose in terms of real income and population. The winners of the US carbon tax are Europe, Japan, and other developed regions. Two forces are at work that explain this. On the one hand, the economic leakage from the US carbon tax benefits regions with comparative advantage in non-agriculture, primarily developed countries. On the other hand, the shift in comparative advantage in the US hurts regions in the rest of the world that are specialized in agriculture.

Table F1: Effect of Carbon Tax in US on the World (No Rebating)

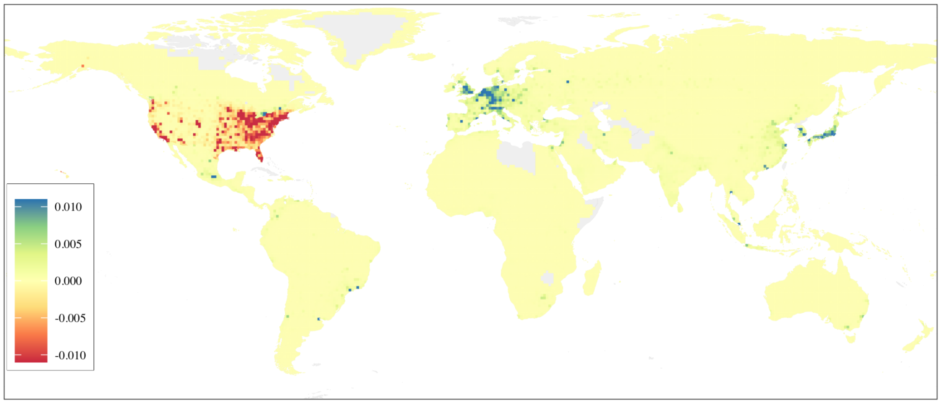
	World		EU		US		Japan		SSA		S. & E. Asia	
	2021	2100	2021	2100	2021	2100	2021	2100	2021	2100	2021	2100
%Δ Income	-0.56	-0.17	1.75	1.73	-5.03	-5	1.76	1.91	-3.07	-3.86	-1.38	-1.05
%Δ Income pc	-0.56	-0.17	-0.15	0.08	-3.28	-3	-0.22	0.13	-0.92	-1.5	-1.13	-0.84
%Δ Welfare	-0.8	-0.5	-0.75	-0.49	-2.73	-2.35	-0.87	-0.44	-2.37	-2.14	-1.61	-1.25
%Δ Population	0	0	1.91	1.66	-1.81	-2.06	1.99	1.77	-2.17	-2.4	-0.26	-0.21
%Δ Agricultural Output	0.13	0.75	0.12	1.26	-1.29	1.55	-0.16	1.22	-0.34	6.63	0.35	1.34
%Δ Non-agric. Output	0.85	1.42	2.78	3.04	-3.36	-3.09	2.54	2.91	0.34	0.63	0.84	1.54
%Δ Emissions	-2.04	-1.69	11.58	10.31	-43.66	-44.31	11.33	10.17	8.92	7.75	9.45	8.68

Note: For different variables and regions of the world, Table displays log difference (*100) between the baseline with a carbon tax and no rebating and a counterfactual without a carbon tax. SSA refers to Sub-saharan Africa, and S. & E. Asia refers to South and East Asia, which includes Bangladesh, Brunei, China, Indonesia, India, Cambodia, Laos, Sri Lanka, Myanmar, Malaysia, Philippines, Thailand, and Vietnam.

Upon impact, the US carbon tax improves real income in Europe by 1.75%, while sub-Saharan Africa sees a decline by 3.86% (Table F1). This reflects Europe attracting more population (+1.91%) and sub-Saharan Africa losing population (-2.17%). In terms of welfare, the world is worse off, both in 2021 (-0.8%) and in 2100 (-0.5%). Although migration from poorer regions to richer regions improves efficiency and welfare, the losses from a carbon tax without rebating dominate. The economic leakage from the US to other developed countries is accompanied by carbon leakage (Figure F3). In the year 2100, carbon emissions are 44% lower in the US, but 10% higher in the EU and Japan. Globally, they drop by around 2% (Table F1).

Overall, the impact of a US carbon tax is similar, both qualitatively and quantitatively, to that of an EU carbon tax, with of course the difference that the roles of the US and the EU are reversed. For example, global real income per capita drops by 0.56% after the introduction of a US carbon tax, whereas it drops by 0.65% if the EU implements a carbon tax. And while a US carbon tax lowers income per capita in the EU by 0.15%, an EU carbon tax lowers income per capita in the US by 0.20%.

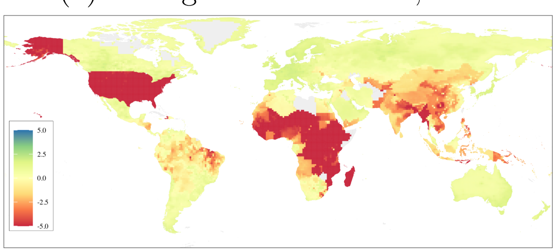
Figure F3: Effect of US Carbon Tax on Emissions around the World (No Rebating), 2021



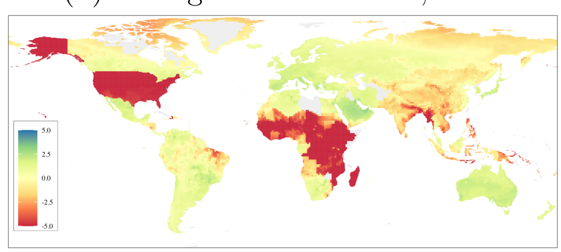
Note: Maps display differences in emission levels (in tCO_2) between the baseline with a carbon tax (and no rebating) and a counterfactual without a carbon tax. Figure D4 shows the equivalent European map.

Figure F4: Effect of US Carbon Tax on Real Income and Population across the Globe (No Rebating)

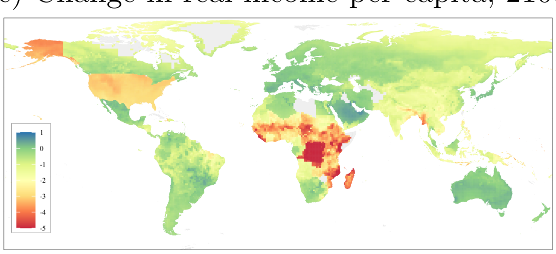
(a) Change in real income, 2021



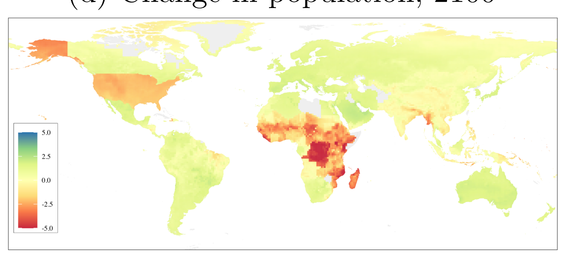
(b) Change in real income, 2100



(c) Change in real income per capita, 2100



(d) Change in population, 2100



Note: Map displays for different variables the log difference (*100) between the baseline with carbon taxes (and no rebating) and a counterfactual without carbon taxes. Panel (a) shows real income in 2021, Panel (b) shows real income in 2100, Panel (c) shows real income per capita in 2100, Panel (d) shows population in 2100.

F.2 Local Rebating: Additional Tables and Figures

Table F2: Effect of US Carbon Tax on Different Regions of the World (Local Rebating)

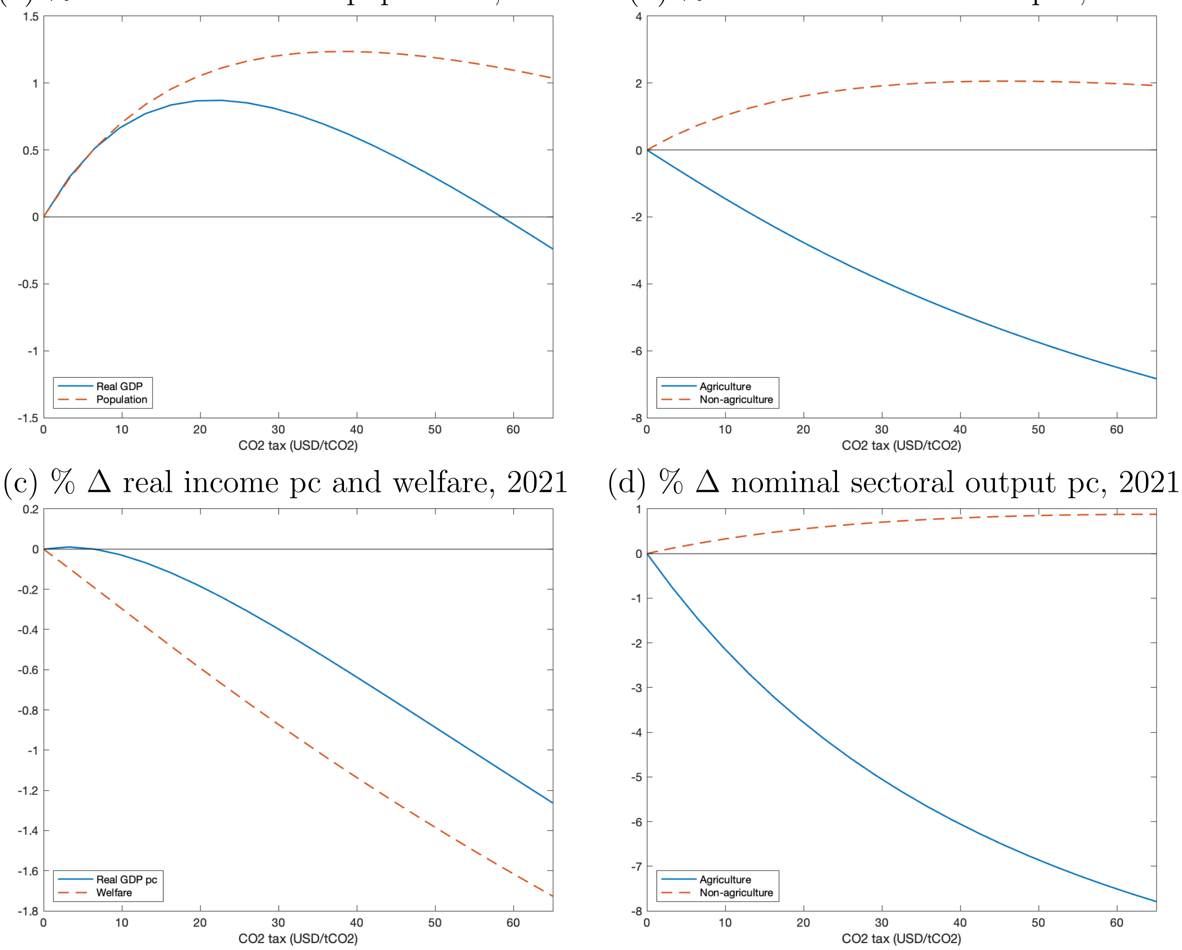
	World		EU		US		Japan		SSA		Asia	
	2021	2100	2021	2100	2021	2100	2021	2100	2021	2100	2021	2100
%Δ Income	0.73	0.91	1.54	1.53	0.59	0.71	1.51	1.71	-3.34	-4.07	-1.51	-1.19
%Δ Income pc	0.73	0.91	-0.21	0.03	-0.64	-0.34	-0.28	0.1	-0.96	-1.52	-1.13	-0.85
%Δ Welfare	0.21	0.49	-0.75	-0.47	-1.14	-0.71	-0.85	-0.41	-2.37	-2.12	-1.57	-1.23
%Δ Population	0	0	1.75	1.5	1.24	1.05	1.8	1.6	-2.4	-2.58	-0.38	-0.34
%Δ Agricultural Output	1.26	1.84	2.15	4.72	-4.9	-3.77	2.59	3.89	0.77	7.06	1.68	2.33
%Δ Non-agric. Output	1.33	1.86	1.22	1.83	2.04	2.02	1.02	2.02	-0.29	0.31	-0.13	0.82
%Δ Emissions	-2.06	-1.7	10.03	9.07	-40.5	-41.36	9.81	9.26	8.45	7.45	8.77	8.2

Note: For different variables and regions of the world, Table displays log difference (*100) between the baseline with a carbon tax and local rebating and a counterfactual without a carbon tax. SSA refers to Sub-saharan Africa, and S. & E. Asia refers to South and East Asia, which includes Bangladesh, Brunei, China, Indonesia, India, Cambodia, Laos, Sri Lanka, Myanmar, Malaysia, Philippines, Thailand, and Vietnam.

Figure F5: Effect of US Carbon Tax on US Economy (Local Rebating), 2021

(a) % Δ real income and population, 2021 (b) % Δ nominal sectoral output, 2021

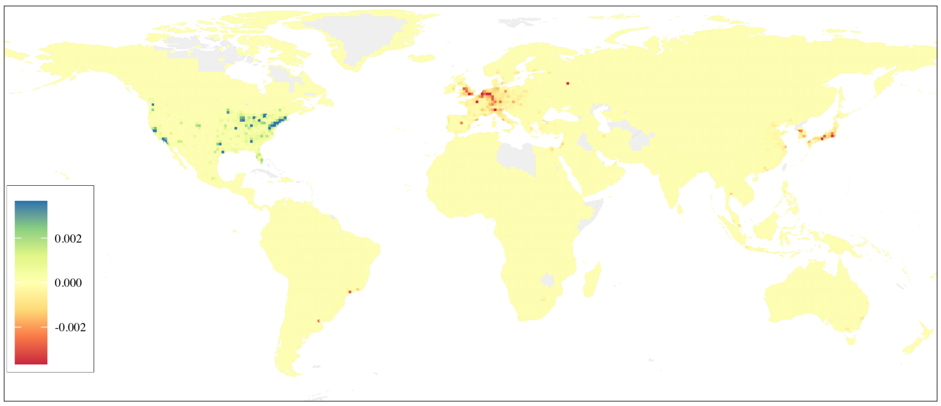
(c) % Δ real income pc and welfare, 2021 (d) % Δ nominal sectoral output pc, 2021



Note: For different EU variables, Figure displays the log difference (*100) in 2021 between the baseline with carbon taxes (and local rebating) and a counterfactual without carbon taxes. Panel (a) shows EU real income and population, Panel (b) shows EU nominal sectoral output, Panel (c) shows EU real income per capita and welfare, and Panel (d) shows EU nominal sectoral output per capita.

Figure F6: Effect of US Carbon Tax on Emissions around the World (Local vs No Rebating), 2021

Δ emissions (local - no rebating), 2021

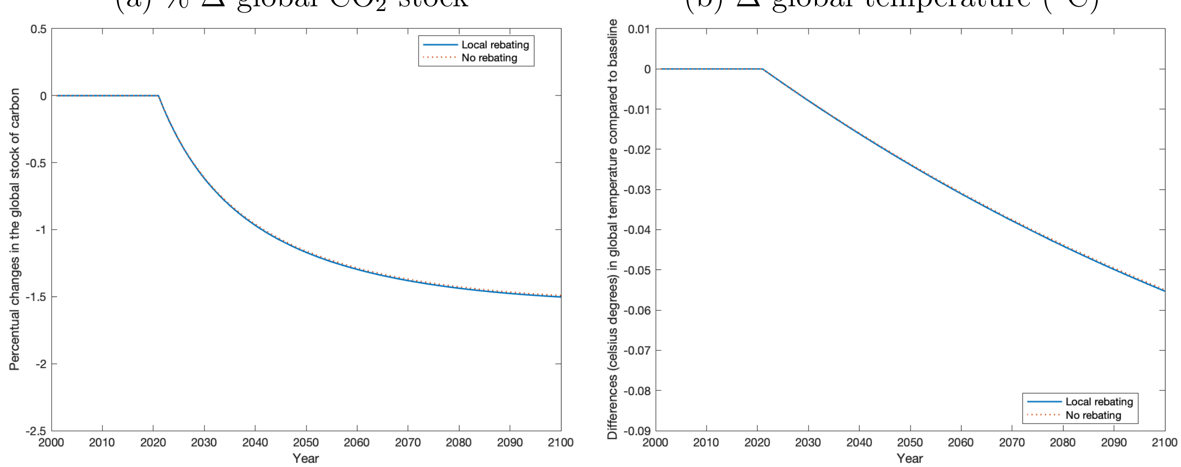


Note: Maps display differences in emission levels (in tCO_2) between the case with a carbon tax (and local rebating) and the case with a carbon tax (and no rebating).

Figure F7: Effect of Different Rebating Schemes of US Carbon Tax on Global CO_2 Stock and Temperature

(a) % Δ global CO_2 stock

(b) Δ global temperature (°C)



Panel (a) displays change in global CO_2 stock under different rebating schemes, and Panel (b) displays change in global temperature (°C) under different rebating schemes.

G Appendix: Solving the Model

The solution method of the model follows closely Conte et al. (2021). In particular, the algorithm to solve for the equilibrium in each period t consists of a 3–level loop that solves for the distribution of the following 4 endogenous variables: $\bar{L}_t(r)$, e_t, $\bar{L}_{At}(r)$, and $w_t(r)$. Ultimately, the first 3 become explicit (but complex), functions of $w_t(r)$, which is the actual endogenous variable that solves for the period–t equilibrium. The nesting structure works as follows:

- **Outer loop:** solves for $\bar{L}_t(r)$ and e_t.
  - **Middle loop:** solves for $\bar{L}_{At}(r)$.
    - **Inner loop:** solves for $w_t(r)$ combining sectoral market clearing conditions:

$$w_t(r)^{1+\theta} = \int_S f(\mathbf{w}_t, \cdot)\, y_t(s)\, ds \quad \forall r. \tag{26}$$

For the inner loop, we proceed as in Conte et al. (2021) and retrieve $y_t(s)$ as an explicit function of $w_t(s)$ only. That allows us to iterate over (26) and solve for the distribution of wages. The main difference between Conte et al. (2021) and our method is that, when doing so, we also retrieve carbon tax revenues as an explicit function of nominal wages. We achieve this by substituting the carbon tax revenues in equation (12) into the nominal income in equation (3). As an illustration, in the case of local rebating, that becomes

$$\begin{aligned} y_t(s) &= \overbrace{w_t(r)\,\bar{L}_t(s) + \left(\Pi_t/\bar{L}\right)\bar{L}_t(s) + R_t(s)\,H(s)}^{\equiv g(\mathbf{w}_t,\cdot)} + b_t(s)\bar{L}_t(s) \\ &= g(\mathbf{w}_t, \cdot) + \sum_{i=1}^{I} \Upsilon_t(s) e_t \frac{\sigma_i}{\gamma_i + \mu_i} \frac{w_t(s)}{(1+\Upsilon_t(s))\, e_t} \bar{L}_{it}(s). \end{aligned} \tag{27}$$

Note the equivalence of all but the last elements of the right hand side with the function $(g(\mathbf{w}_t, \cdot))$ in Conte et al. (2021). Then, with the guesses for sectoral employments $L_{it}(r)$ and energy prices e_t, it is possible to iterate on (26) and retrieve the equilibrium distribution of wages.

We then proceed with the middle loop by plugging the solution for wages from the inner loop into the sectoral market clearing conditions. This yields sectoral employment levels, $\bar{L}_{At}(r)$, using an analogous iterative procedure. Finally, the outer loop uses the previous results together with migrations shares and energy market clearing conditions to obtain an update for the population distribution and energy prices, $\bar{L}_t(r)$ and e_t. We iterate this 3–level procedure until all conditions hold simultaneously.