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

A unilateral carbon tax trades off the distortionary costs of taxation and the future gains from slowing down global warming. Because the cost is local and immediate, whereas the benefit is global and delayed, this tradeoff tends to be unfavorable to unilateral carbon taxes. We show that this logic breaks down in a world with trade and migration where economic geography is shaped by agglomeration economies and congestion forces. Using a multisector dynamic spatial integrated assessment model (S-IAM), this paper

generated by the tax start to dominate and the EU economy shrinks, although global welfare gains continue for relatively high levels of carbon taxes.

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 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 eastern Europe move more into agriculture. Over time, these patterns are reinforced, with the exception of Scandinavia. There, future agricultural productivity is depressed by a carbon tax that limits global warming. 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 higher-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, we consider several alternatives. 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 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, less migrants come 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.

Our work is related to the large literature on the climate and welfare effects of carbon taxes. Because a decrease in carbon emissions causes a global externality, a central result of this literature is that carbon taxes are only welfare-improving 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.[2]

Our work 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 S-IAMs in two-dimensional space include Desmet et al. (2018),

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[2] See also Weisbach et al. (2022) and Kortum and Weisbach (2021) for an analysis of optimal unilateral carbon policy in a multi-country economy.

Conte et al. (2021), Cruz and Rossi-Hansberg (2021) and Cruz (2021). Other papers in that vein are Conte (2020) and Nath (2020), though they are static and ignore migration as a key adaptation strategy to climate change. Balboni (2019) 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 presents a description of our model, describes the local effects of carbon taxes, and discusses the quantification. Section 3 specific cost, $m_2(s)$, so that $m(r;s) = m_1(r)\,m_2(s)$. Remaining in the same place is costless, and so $m(r;r) = m_1(r)\,m_2(r) = 1$. 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, $w_t(r)$, an agent residing in r at time t gets a proportional share of local land rents, $R_t(r)\,H(r)/L_t(r)$, as well as a proportional share of global profits from the resource extraction sector, Π_t/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

$$u_t(r) = a_t(r)\,\frac{w_t(r) + \Pi_t/L + R_t(r)\,H(r)/L_t(r) + b_t(r)}{\prod_{i=1}^{I} P_{it}(r)^{\theta_i}}; \tag{2}$$

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

$$y_t(r) = w_t(r)\,L_t(r) + \Pi_t/L\;L_t(r) + R_t(r)\,H(r) + b_t(r)L_t(r). \tag{3}$$

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

$$q^{\omega}_{it}(r) = L^{\omega}_{\nu,it}(r)^{\xi_i}\, z^{\omega}_{it}(r)\, L^{\omega}_{it}(r)^{\mu_i}\, E^{\omega}_{it}(r)^{\sigma_i}\, H^{\omega}_{it}(r)^{1-\xi_i-\mu_i-\sigma_i}; \tag{4}$$

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

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

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 $L_{it}(r)$ is total sectoral employment, $L_{\nu,it}(r) + L_{it}(r)$. We assume that $\alpha_i > 0$ so average productivity is increasing in local density, $L_{it}(r)/H_{it}(r)$. 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

$$\tau_{it}(r) = L_{\nu,i,t-1}(r)^{\lambda_i}\left[\int_S e^{-\partial\,\mathrm{dist}(r,s)}\,\tau_{i,t-1}(s)\,ds\right]^{1-\gamma_i}\tau_{i,t-1}(r)^{\gamma_i}; \tag{6}$$

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

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

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 $\tau_t(r)$ 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

$$p^{\omega}_{it}(r;r)\, q^{\omega}_{it}(r) - w_t(r)\left(L^{\omega}_{\phi,it}(r) + L^{\omega}_{it}(r)\right) - \left(1 + \tau_t(r)\right) e_t E^{\omega}_{it}(r) - R_t(r)\, H^{\omega}_{it}(r) \tag{8}$$

subject to the production function (4), where e_t denotes the global price of energy and $p^{\omega}_{it}(r;r)$ 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 $E_t = e_t^{\epsilon}$, where $\epsilon \in (0;1)$. We ignore resource extraction costs, so that profits are equal to revenue in the energy sector, $\pi_t = e_t E_t = e_t^{1+\epsilon}$.

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,

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

where $\Delta(r)$ 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

$$A_t(r) = \sum_{i=1}^{I} \tau_t(r) e_t E_{it}(r) = \sum_{i=1}^{I} \tau_t(r) e_t \frac{\nu_i}{\mu_i + \nu_i} \frac{w_t(r)}{\left(1 + \tau_t(r)\right) e_t} L_{it}(r) \tag{12}$$

where the second equality comes from the firm's profit maximization problem in sector i and location r. We consider four different schemes for how the government of jurisdiction J rebates carbon tax revenues. First, carbon tax revenues may be lost, in which case

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 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 $_i$. 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° × 1° cells, and focus on two sectors, agriculture and non-agriculture. At that level of spatial resolution, our quantification 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 A1 and come mostly from

Figure 1: Temperature Discount in Agriculture and Non-Agriculture

estimates with our parameter values for the share of agriculture in 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%.

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 $(r) = 0.863$, 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.[6]

Sectoral specialization. Figure 2 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 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 as well as in Ireland. The northernmost peripheral regions do not experience this gain in agriculture, as the carbon tax limits the rise in temperature that benefits them. 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 that the shift in comparative advantage is more important: neighboring regions mostly experience an increase in non-agricultural output. For regions further afield, Appendix Figure B1 and Figure B2 display similar maps for the entire world. The model-predicted numbers for different regions of the world are given in Table

Figure 4: Effect of Carbon Tax on EU Economy (No Rebating), 2021

(a) % real income and population, 2021

(b) % nominal sectoral output, 2021

(c) % real income pc and welfare, 2021

(d) % 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 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.

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 0.1% in the US and by 0.03% in Japan, and it declines by 2.36% in sub-Saharan Africa and by 1.42% in South and East Asia (see Table 1). Overall, the winners do not compensate for the losers: in the absence of rebating, global real income per capita declines by 0.67% 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 1.17% in the EU, by 3.83% in sub-Saharan Africa and by 0.2% in South and East Asia, whereas population is predicted to increase by 3% in the US (Table 1).

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.

Figure 7: Effect on Carbon Tax on Emissions around the World (No Rebating), 2021 and 2100

(a) Change in emissions, 2021

(b) Change in emissions, 2100

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 B3 shows the equivalent European map.

Figure 7 shows a global map of the changes in emissions in 2021 and 2100. Across Europe we see a decline in emissions, especially in the non-agricultural c.005 5O0btural

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 8: 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

Figure 9: Change in Sectoral Output Due to Carbon Taxes (Local Rebating), Europe

(a) % Agriculture, local rebating, 2021

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

(c) % Agriculture, local rebating, 2100

(d) % 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.

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, except in Scandinavia. There, the growing comparative advantage in agriculture due to global warming is eroded by carbon taxes that limit emissions and keep temperatures lower. 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 10 Panel (a) shows that the EU

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 1.25% in response to the carbon tax.

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 outmigration 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. Table 2 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 (-1.34%), than in high-income regions, such as the European Union (-0.5%) and the US (+0.07%). Welfare effects in these regions follow similar patterns.

Figure 12: Effect of Carbon Tax on Real Income per Capita and Population across the Globe (Local Rebating)

(a) % real income pc, 2100

(b) % population, 2100

Note: For different variables, 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.

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 Table 2, 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 (Figure 13, Panel (a), and Table 2). 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 2.2% with or without rebating.

Figure 13: Effect on Carbon Tax on Emissions around the World (Local vs No Rebating), 2021 and 2100

(a) emissions (local - no rebating), 2021

(b) emissions (local - no rebating), 2100

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).

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, 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, , and on the degree of preference heterogeneity, .

Figure 14: Effect of Different and on EU Outcomes with Local Rebating, 2021

(a) % EU real income, 2021 ( ) (b) % EU population, 2021 ( )

(c) % EU real income, 2021 ( ) (d) % EU population, 2021 ( )

Note: Figure displays the effect of EU carbon taxes in the case of local rebating on EU real income and population for different values of (Panels a and b) and for different values of (Panels c and d).

If the trade elasticity 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 we should see a greater expansion of the EU. Figure 14 Panels (a) and (b) show the effects for values of that are 50% higher and 50% lower than the baseline[8]. Consistent with our argument, we indeed find larger positive effects on EU population and EU real income for smaller values of .

If locational preference heterogeneity is low, the elasticity of migration to income differences is large. In that case, the increase in income in the EU core induced by the carbon tax attracts more migrants, both from within the EU 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 , the greater these effects should be. Figure 14 Panels (c) and (d) plots the effects for both higher (+50%) and lower (-50%) values of . In line with our argument, the EU grows more in terms of population and real income for smaller values of .

5 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 15: Change in Sectoral Output Due to Carbon Taxes: EU Rebating vs Local Rebating

(a) % agr., EU – local rebating, 2021

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

Figure 16: Effect of Different Rebating Schemes on EU and World Economy, 2021

(a) % EU real income, 2021

(b) % EU population, 2021

(c) % world real income pc, 2021

(d) % world welfare, 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), EU population (Panel b), world real income per capita (Panel c), and world welfare (Panel 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 16, panels (a) and (b)). In fact, the drop in income and population

Figure 17: Effect of Carbon Tax across the Globe (Developing countries vs Local Rebating)

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

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

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 18). This is due to developing countries rebating lowering world production more than other rebating arrangements. The effects are still small in 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.[9]

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

Table 3: 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												
% Real GDP	0.62	1.12	0.13	0.87	1.69	2.65	1.49	2.44	-3.49	-6.55	-1.52	-1.86
% Real GDP pc	0.62	1.12	-1.75	-1.49	-0.19	0.1	-0.28	0.03	-0.94	-2.36	-1.12	-1.32
% Welfare	0.14	0.46	-2.51	-2.67	-0.8	-0.69	-0.85	-0.74	-2.39	-3.38	-1.53	-1.9
% Population	0	0	1.92	2.4	1.89	2.55	1.78	2.41	-2.58	-4.3	-0.4	-0.54
% Agricultural Output	1.22	2.62	-2.85	-1.97	2.33	5.47	2.81	6.84	1.01	2.78	2.22	4.05
% Non-agric. Output	1.25	2.65	1.39	2.24	1.34	2.94	0.45	2.35	-0.51	0.09	-0.68	0.49
% Emissions	-2.17	-2.68	-40.63	-38.84	10.62	14.75	9.66	14.1	8.73	11.63	8.77	12.59

Panel B: DevelopingA% 14.n1m2a(0.49)]TJ 0 -11.955 TD [(%)-333.005 (Rea)-0.99462(l- /T2994 5308)]1-9709 (cos) 2.39 0909 72.65 1.49-13

pulation

(0.1420167.002 (-2.36))-1533.003(-0 (25)-1533.992-1.1149)-2199.998 0 .66 0.35 1375 -1336 -56(24)-1699.993997 (6)-16

6 Conclusion

Unilateral carbon policy has an effect on the spatial distribution of economic activity and its efficiency.

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A Appendix: Additional Tables

Table A1: Parameter Values

Parameter	Target/Comment
1. Preferences	
$= 0:96$	Annual discount factor
$= 0:75$	Elasticity of substitution of 4 [1]
$= 0:32$	Relation between amenities and population[1]
$= 0:5$	Elasticity of migration flows with respect to income [1]
$= 1:8$	Subjective well-being parameter[1]
$_{A} = 0:051$	Data on agricultural and total output
$_{M} = 0:949$	Data on agricultural and total output
2. Technology	
$_{A} = 0$	No agglomeration externality in agriculture
$_{M} = 0:01$	Agglomeration externality in non-agriculture [1]
$= 6:5$	Trade elasticity [1]
$_{A} = \ _{M} = 0:6$	Labor share in agriculture and non-agriculture[2]
$_{A} = 0:001$	Growth rate of agricultural productivity [3]
$_{M} = 0:0002$	Growth rate of non-agricultural productivity [3]
$_{A} = 0:04$	Energy share in agriculture (Schnepf, 2004; Australian Bureau of Statistics, 2021)
$_{M} = 0:07$	Energy share in non-agriculture (Grubb et al., 2018; King et al., 2015)
$= 0:993$	Technology diffusion[1]
$@ = 0:004$	Spatial decay of diffusion[4]
$= 0:25$	Energy supply elasticity[2]
3. Temperature and carbon cycle	
$g_{A}^{opt} = 19:9^{\circ}C$	Optimal temperature in agriculture [2]
$g_{A}^{var} = 7:28^{\circ}C$	0.1% of= di.6ntn.04 k 26.022t1_1 9.963 Tl99 (agriculca6ntns1_1 9.963 Tb9 (agriculptihare)-3lshare)-3T

Figure B2: 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 B3: Change in Emissions in the EU Due to Carbon Tax (No Rebating)

(a) Difference in emissions (tCO_2), 2021

(b) Difference in emissions (tCO_2), 2100

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.

B.2 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 ( ) and the degree of locational preference heterogeneity ( ). Figure B4

C 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*