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A global carbon tax? Why firm mobility and heterogeneity matters*

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Abstract

This paper investigates the multiple effects of a global carbon tax in an imperfectly competitive economy characterized by asymmetrically sized countries, mobile and heterogeneous firms, and international trade. In the short run, the global tax produces only Pigouvian effects, thereby reducing emissions, as argued in the literature. However, in the long run, when firms are mobile we uncover several less friendly impacts of the tax that crucially depend on the level of trade costs. In fact, agglomeration and relocation effects of dirty or clean firms may greatly reduce or magnify the effects of the tax. In addition, we show that a global tax instrument may actually eliminate the most environmentally-friendly spatial locations when trade costs are high. Given the urgent need for a global environmental policy that curbs emissions, our findings highlight the relevance of trade costs, which may heavily impact the effectiveness of such a policy.

Keywords: Global carbon tax; Heterogeneous firms; International trade; Firm location.

JEL Classification: F12, F15, F18, Q28.

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1 Introduction

"The scientists tell us that world temperatures are rising because humans are emitting carbon into the atmosphere. Basic economics tells us that when you tax something, you normally get less of it. So if we want to reduce global emissions of carbon, we need a global carbon tax. Q.E.D." New-York Times, October 16th, 2007

This paper examines the effects of a global carbon tax and its ability to curb carbon emissions in a globalized economy characterized by *heterogeneous* countries and an uneven spatial distribution of *heterogeneous* and *mobile* firms. There exists a general agreement among economists about the global carbon tax being the most economically efficient way to reduce greenhouse-gas emissions and keep global temperatures within the targets of the Paris climate agreement (Stiglitz et al., 2017). A global carbon tax is seen as an ideal instrument because it addresses both domestic and transboundary pollution. An international carbon tax produces Pigouvian effects that reduce polluting production. In addition, a global tax avoids the well-known carbon leakage issue. In a globalized world, production activities can shift to countries with more lax environmental policies, such that decentralized environmental policies are less effective in reducing emissions. Hence, a global carbon tax is desirable because it would be neutral to any delocalization strategy of firms. Unfortunately, in these statements various features of the open economies that compose the world today are overlooked.

Is the Pigouvian effect the only observable effect when countries show different population sizes and firms are heterogeneous and mobile? If countries and firms are heterogeneous, a unique tax instrument cannot offset the existing difference in profitability in different locations when firms produce under increasing returns to scale. Thus, market size effects persist independently of the global tax. It follows that changing the profit margin of mobile firms may lead to the agglomeration or dispersion of firms, with relevant consequences for the environment. Agglomeration in large countries ultimately translates into more production and thus more pollution. In addition, changing the firm margins via a global policy moderates the intensity of traded quantities. In fact, the level of the global carbon tax may render international trade less convenient, which in turn changes the quantities produced and the corresponding pollution. It appears then critical to ask the following questions. How does the heterogeneity of countries and mobile firms modulate the efficiency of a global tax in the presence of increasing returns to scale? When trade policies accompany a global carbon tax, do trade wars or trade agreements that change trade costs accelerate or invalidate the effects of a carbon tax? The purpose of this paper is to provide insight into the answers to these questions.[1]

We advance the hypothesis that although a global carbon tax is an attractive environmental measure, it may be subject to debate because it has various other effects such as a significant impact on the locations of heterogeneous firms when countries have asymmetric population sizes and the industrial sector is imperfectly competitive. In addition, a global carbon tax can also impact foreign trade patterns worldwide, not

[1] Carbon taxes raise concerns also with respect to equity. They may increase inequality since low-income households spend a more significant share of their income on carbon-intensive goods(Fremstad and Paul, 2019).

necessarily favoring lower pollution levels. To evaluate these effects of global taxation, we use a model of a globalized economy characterized by international trade and firm mobility.

Formally, we build a trade model with two asymmetrically-sized countries in which heterogeneous and mobile firms produce under increasing returns to scale, inspired by Okubo et al. (2010). Carbon dioxide (CO_2) emissions are a by-product of the production activities of manufacturing firms, which engage in international trade. Therefore, our model accounts for the fact that CO_2 emissions, embodied in international trade, are a significant contributing factor to the increase in emissions, especially in countries such as China (Ahmad and Wyckoff, 2003; Peters and Hertwich, 2008; Weber et al., 2008; Lin and Sun, 2010).[2] Moreover, manufacturing firms are assumed to be either clean or dirty, depending on the technology they use. Finally, firms have a fixed location in the short run but they are free to relocate in the long run. It follows that a global carbon tax policy affects the location choices of clean and dirty firms in different ways. This framework allows for the analysis of the location decisions of dirty and clean firms, the effect of a carbon tax on trade patterns, and finally, the efficiency of a global carbon tax in reducing global emissions.

We first analyze the short run and determine the effects of a global policy when firms are immobile. This scenario highlights the Pigouvian effect of the global carbon tax. Then, we characterize the stable location equilibria of clean and dirty firms in the long run, according to the trade cost levels. Our main results for the long-run analysis can be summarized as follows. First, trade liberalization leads to a greater agglomeration of firms in the larger country because of a market size effect. In turn, agglomeration raises global emissions due to the large market size. This finding suggests that trade liberalization is detrimental to the environment and, therefore, the need for a global carbon tax is higher as trade intensifies. However, a global carbon tax is not a spatially neutral policy instrument. The tax itself may favor the emergence of more agglomerated or more disperse spatial configurations when market sizes are strongly asymmetric. Hence, the beneficial Pigouvian effects of a global carbon tax might be dampened or magnified depending on the direction of the relocation effects. If trade costs are such that the carbon tax brings a dispersion of firms and thus relocation effects go along the same direction as the Pigouvian effects, then the global tax is very effective. However, depending on trade cost levels, the effect of a global tax may be quite small. This finding highlights the importance of market globalization, which may heavily impact the effectiveness of a global tax instrument. Finally, there exists a threshold value of the carbon tax above which trade patterns are considerably affected; in fact, firms cease to trade in foreign countries. We show that this situation is a dark side of the effects of a global carbon tax. Such a no-trade effect may paradoxically lead to the disappearance of the most environmentally-friendly spatial locations because some firms react by relocating to the large country in order to restore their margin on the foreign market. Importantly, a sufficiently low level of carbon tax has only positive effects on the environment: it lowers pollution emissions in any equilibrium spatial configuration, but the magnitude of the reduction in CO_2 emissions again depends on how large trade costs are.

Our contribution relates to but remains very different from previous literature on the pollution haven

[2]Such an analysis builds on the distinction between emissions based on consumption and those based on production (Peters, 2008).

hypothesis, according to which pollution-intensive industries move to countries with less stringent environmental regulation. Previous contributions generalize the reciprocal dumping model by endogenizing the number of plants and their locations (Markusen et al., 1993). Firms can react to a tightening of environmental policies by shutting down their plants and transferring production to plants in another country.[3] Zeng and Zhao (2009) develop a model in which manufacturing production generates cross-border pollution and location choices driven by international differences in environmental policy and agglomeration forces.[4] The authors demonstrate that these manufacturing agglomeration forces alleviate the benefits of locating in a pollution haven.[5] However, we consider a global carbon tax, which leaves no room for the pollution haven hypothesis in our setting. We rather stress the role of the heterogeneity of countries and firms. We contribute to this literature by analyzing whether the centralization of environmental policy through a global carbon tax avoids relocation effects and further analyze the tax's ability to improve environmental quality. Surprisingly, we show that with a unique global tax, dispersion and location in small countries is environmentally friendly because such a configuration avoids agglomeration in large markets and high pollution levels.

Our paper also contributes to the broad literature on the environmental impact of trade liberalization. Since the work of Grossman and Krueger (1993), it has become well known that trade liberalization can affect the environment through different channels. Whether the overall impact will be positive or negative has given rise to many theoretical and empirical contributions (Sturm, 2003). For instance, Antweiler, Copeland, and Taylor (2001) consider pollution as a public bad and develop a Ricardian model allowing both income and factor endowment differences across countries.[6] Their empirical results indicate that the overall impact of trade on environmental quality is positive but small. Our paper complements this literature by showing how trade liberalization influences the environment through firm relocation strategies (rather than through technological upgrading behavior) in an imperfectly competitive economy. Specifically, we show that trade cost levels influence both the level of global emissions and the ability of such a policy instrument to improve environmental quality. Importantly, the setting we propose allows analyzing how global environmental measures affect international trade patterns. We isolate a novel effect of the carbon tax on trade patterns not due to regulation externalities among countries competing for foreign direct investment (FDI) or capital.

The remainder of the paper is organized as follows. In Section 2, we develop a model of international trade with firms that have different marginal costs and emission intensities, and in Section 3 we describe the outcome and pollution levels when firms are immobile. In Section 4, we describe the location choices

[3]Taking into account the fixed cost to set up a plant, Motta and Thisse (1994) demonstrate that such a relocation is less likely to occur. As a consequence, the decentralization of the environmental policy leads the government to behave non-cooperatively. Depending on the level of disutility associated with pollution, the government chooses either a strategy of environmental dumping or a strategy "Not in My Back Yard" type (Markusen and al., 1995).

[4]Agglomeration forces stem from the assumption of increasing returns to scale and asymmetric market sizes.

[5]Empirical evidence related to the pollution haven hypothesis is also mixed (Jeppesen et al. 2002; Eskeland and Harrison, 2003; Ederington et al., 2005). Interestingly, Levinson and Taylor (2008) raise several methodological issues that help explain why empirical studies have difficulty demonstrating the existence of this effect.

[6]Therefore, the influence of differences in factor endowment can dominate the impact of differences in environmental policy on comparative advantage.

of firms in the long run and the ability of a global carbon tax to reduce global emissions. In Section 5, we briefly examine the effects of our initial central hypothesis. The final section concludes the paper.

2 The model

Consider an economy with two countries ($i = H; F$), two production factors, labor and physical capital, and two sectors in which firms produce two goods: *i*) an industrial one, x, using a polluting technology, and *ii*) a numéraire good z whose production does not involve carbon emissions. Country H is supposed to host a share $\lambda > 1/2$ of the total population l, and each individual is equally endowed with one unit of labor and an equal share of the capital stock.[7] Residents work and consume in the country in which they live but invest their capital either in country H or F. The spatial distribution of firms is given in the short run but it is endogenous in the long run, dictated by the difference in return to capital between countries. A supranational authority implements a global carbon tax t on the per-unit carbon emissions for environmental purposes.[8] Pollution is considered a *global* public bad: the utility loss induced by one unit of emissions from country i is the same wherever individuals are located. As an example, pollution through CO_2 emissions is a global problem that justifies an internationally-coordinated mitigation policy such as a global carbon tax.

Preferences For analytical tractability, we assume that individuals share the same quasi-linear utility function u_i with respect to the numéraire z and the manufactured good x, both goods being homogeneous.[9] A consumer residing in country i thus solves the following problem:

$$\underset{x_i}{Max}\ u_i \equiv \left(a - \frac{\beta x_i}{2}\right) x_i - \gamma E + z_i \tag{1}$$

$$s.t. \quad \bar{z} + y_i = x_i p_i + z_i \tag{2}$$

where $a > 0$, x_i is the individual consumption level of the manufactured good, z_i is the individual consumption of the numéraire, $\bar{z}$ is the individual endowment in the numéraire, and y_i is the individual income given by the sum of the wage rate and the individual return to capital. We assume that the initial endowment $\bar{z}$ is large enough for the individual consumption of the numéraire to be strictly positive at the market outcome. Finally, γ captures the individual damage arising from the total emissions of the manufacturing sector (E), which are assumed to spill over across the two countries.[10]

Given (1) and (2), the individual demand x_i for the manufactured good is given by:

$$x_i = \frac{a - p_i}{\beta}, \quad \forall\ i = H, F. \tag{3}$$

[7] Given the existence of quasi-linear preferences, our results would remain valid under the assumption of foreign capital ownership.

[8] In our model, the individual demand for the industrial good is not subject to income effects. Accordingly, the market outcome does not depend on the use made of tax revenues. Therefore, for simplicity we abstract from tax revenues.

[9] Although the income effect is erased with quasi-linear utility, Dinopoulos et al. (2007, p.22) show that this type of preference behaves reasonably well in models of international trade.

[10] As in Markusen, Morey, and Olewiler (1993, 1995), Pflüger (2001), and Ishikawa and Okubo (2017), pollution is perceived as being exogenous by consumers, and therefore does not influence their consumption choice.

Aggregating the demand for good x over all consumers yields the total market demand curves in each country:

$$X_h = \frac{\lambda l}{\beta}(a - p_h) \text{ and } X_f = \frac{(1-\lambda)\, l}{\beta}\,(a - p_f) \tag{4}$$

Technology and market structure The numeraire z is costlessly traded and produced under constant returns to scale where one unit of labor is required to produce one unit of output. Thus, its price as well as the individual wage rate are equal to one in each country.

In contrast, good x is produced under increasing returns to scale, in Cournot competition. The manufactured good x is traded with cost and markets are segmented (as in Brander and Krugman, 1983). Each firm incurs a trade cost of $\tau > 0$ units of the numéraire per unit of good x shipped between the two countries.

We consider two types of firms, *clean* (c) and *dirty* (d), whose per-unit levels of carbon emission are ε^k, with $k = c, d$, and $\varepsilon^c < \varepsilon^d$. Hereafter, the superscript k refers to a firm's type in terms of emission intensity. There is a share $\mu > 1/2$ of dirty firms in the economy, whereas the remaining firms are clean.[11] Firms face a marginal cost denoted by m^k, $k = c, d$, with $m^c > m^d$, which can be defined in broad terms as the structural requirement in labor for production, including the potential labor requirement for pollution abatement.[12] It follows that the total marginal cost of a dirty firm is $t\varepsilon^c + m^c$ while that of a clean one is $t\varepsilon^d + m^d$. In the benchmark setting, we focus on the scenario where $t\varepsilon^c + m^c > t\varepsilon^d + m^d$, namely $t < \bar{t} \equiv (m^c - m^d)/(\varepsilon^d - \varepsilon^c)$. This implies that clean firms bear the highest tax-inclusive marginal cost. While it would also be empirically relevant to assume that dirty firms are less productive or have a higher tax-inclusive marginal cost, our main results would remain valid under this alternative scenario, as discussed in Section 5.

Our focus is on the interplay between trade and carbon tax, hence we limit our analysis to trade cost levels that are low enough for all firms to be profitable on the export market, regardless of their type and marginal cost.[13]

3 Short-run analysis $-$ immobile firms

In the short run, a firm's location is given. There are n_h firms located in the large country H, and the rest, $n - n_h$, are located in F, with n being the total number of firms. We now examine the market solution, optimal price, and quantities supplied in each country and the corresponding level of pollution. This setting is reminiscent of previous theoretical studies looking into the effects of a global carbon tax and assuming fixed locations.

[11] We assume that the share of dirty firms is higher than 1/2 so that there is an important environmental concern in the economy, motivating the implementation of the carbon tax. We discuss this assumption in Section 6.

[12] Pollution abatement technologies may involve design costs for a new process of production but also managerial effort for the required paperwork, thereby increasing the marginal cost.

[13] We analyze the behavior of exporting firms specifically because they are more mobile, but also because of the significant share of CO_2 emissions that are reputed to be embodied in production for export. According to Weber et al. (2008), approximately one-third of Chinese emissions were caused by the production of exports in 2005, versus 12% in 1987 and 21% in 2002.

3.1 Market solution

Because of market segmentation, each firm determines a specific quantity to trade to the country in which its product is sold. The net profits of a k-type firm located in country i and selling its good in both countries i and j is given by

$$\pi_i^k = (p_i - m^k - t\varepsilon^k)x_{ii}^k + (p_j - m^k - t\varepsilon^k - \tau)x_{ij}^k - r_i \tag{5}$$

where x_{ii}^k is the quantity the k-type firm supplies to domestic consumers, x_{ij}^k is the quantity it sells to foreign consumers and r_i is the rental rate of capital in country i. The rental rate is country-specific only in the short run.

Maximizing (5) and taking into account demand (4) yields the following output choices x_{hh}^k and x_{ff}^k:

$$x_{hh}^k = \frac{\lambda l}{\beta}\left(p_h - m^k - t\varepsilon^k\right) \text{ and } x_{hf}^k = \frac{(1-\lambda)\,l}{\beta}\left(p_f - m^k - \tau - t\varepsilon^k\right) \tag{6}$$

for a k-type firm located in country H, and

$$x_{ff}^k = \frac{(1-\lambda)\,l}{\beta}\left(p_f - m^k - t\varepsilon^k\right) \text{ and } x_{fh}^k = \frac{\lambda l}{\beta}\left(p_h - m^k - \tau - t\varepsilon^k\right) \tag{7}$$

for a k-type firm located in country F. Because of trade costs, a firm sells less on the export market than its native rival does, $x_{fh}^k = x_{hh}^k - l\lambda\tau/\beta$, regardless of the firm's type. Inspection of the output choices shows that the higher the market size λ, the higher the output supply for consumers of country H. This is the *market size effect* that attracts firms to large markets.

Let n_i^k denote the number of k-type firms in country i. Solving for the market clearing condition for each country, the equilibrium prices in the short run are:

$$p_i^* = \frac{a + n_j\tau + n\omega}{n+1}, \; i = h, f \tag{8}$$

where $\omega \equiv (t\varepsilon^c + m^c)(1-\mu) + \left(t\varepsilon^d + m^d\right)\mu$ is the average tax-inclusive marginal cost in the economy.

Given the above equilibrium quantities and prices, to focus on equilibrium configurations in which bilateral trade flows occur for all firms, we set an upper limit τ_{trade} on the trade costs:

$$\tau < \tau_{trade} \equiv \frac{a - m^c(n+1) + m^d n + nt\left(\varepsilon^d - \varepsilon^c\right) - t\varepsilon^c}{(n+1)}$$

with $a > \bar{a} \equiv m^c(n+1) - m^d n - t\left(n(\varepsilon^d - \varepsilon^c) - \varepsilon^c\right)$.[14]

Simple comparative statics shows that optimal prices, p_i^* $i = h, f,$, decrease with the number of firms located in the country, as competition becomes fiercer $(\partial p_i^*/\partial n_j > 0)$. This is the well-known *competition effect*. This latter effect acts as a dispersion force on firm locations, in contrast to the *market size effect* that rather encourages the agglomeration of firms in the large country. As for the effect of the global carbon tax,

[14] To find τ_{trade}, as in Okubo et al. (2010) we require positivity of the export margin of a clean firm who has the highest tax-inclusive marginal costs on the largest market $(p_h^c - m^c - \tau - t\varepsilon^c)$ when all other firms are dirty $(\mu = 1)$ and located in the largest country as well $(n_f = 0)$.

it augments optimal prices ($\partial p_i/\partial t > 0, i = h, f$) through a *tax-incidence effect*. While the global carbon tax always deteriorates the margins of dirty firms, it also reduces the margins of clean firms if and only if:

$$n < \frac{\varepsilon_c}{\varepsilon_d - \varepsilon_c}. \tag{9}$$

Hereafter, we assume that the latter inequality holds in order to rule out an unusual positive effect of the tax on clean firms' margins. Therefore, despite the incidence effect, the global carbon tax always exerts a negative impact on the supplied quantity through a *Pigouvian effect* due to reduced firms' margins (i.e., $\partial x_{ij}/\partial t < 0, i, j = h, f$.)

Pollution in the short run We turn now to pollution and its determinant in the short run. We first investigate the level of emissions at the firm level, and then we move to the global level of emissions for dirty and clean firms.

Using expressions (6) and (7), we find the level of emissions E_h^k and E_f^k of a $k-$type firm located in country H:

$$E_h^k = x_{hh}^k + x_{hf}^k = \frac{\lambda l}{\beta}\left(p_h^* - m^k - t\varepsilon^k\right) + \frac{(1-\lambda)\, l}{\beta}\left(p_f^* - m^k - \tau - t\varepsilon^k\right);$$

and located in country F :

$$E_f^k = x_{ff}^k + x_{fh}^k = \frac{(1-\lambda)\, l}{\beta}\left(p_f^* - m^k - t\varepsilon^k\right) + \frac{\lambda l}{\beta}\left(p_h^* - m^k - \tau - t\varepsilon^k\right).$$

Observe that

$$E_h^k - E_f^k = \frac{l\tau}{\beta}\left(2\lambda - 1\right) > 0 \tag{10}$$

Therefore, individual emissions are always higher in the large country because firms there meet a larger demand. Importantly, the difference in individual emissions $E_h^k - E_f^k$ decreases with trade liberalization. Given country i, as expected the emissions from a clean firm are lower than those from of a dirty firm under our condition $t < \bar{t}$.[15]

To identify the role of the global carbon tax, we examine the effect of the tax on the emissions of clean and dirty firms according to their location. Formally, we verify that:

$$\frac{dE_h^c}{dt} = \frac{dE_f^c}{dt} = \frac{l}{\beta\,(n+1)}\left(n\mu\left(\varepsilon^d - \varepsilon^c\right) - \varepsilon^c\right) < 0$$
$$\frac{dE_h^d}{dt} = \frac{dE_f^d}{dt} = \frac{l}{\beta\,(n+1)}\left(n\,(1-\mu)\left(\varepsilon^c - \varepsilon^d\right) - \varepsilon^d\right) < 0$$

The carbon tax exerts a total negative impact on emissions in the short-run through its influence on firm margins. This is because the Pigouvian effect of the tax does more than compensate the tax-incidence effect that increases optimal prices. In addition, the negative impact of the carbon tax is stronger for dirty firms.
We now turn to the analysis of total emissions by type of firm. The total emissions of clean firms and dirty firms for a given spatial location are, respectively,

$$E^c = \left[\left(x_{hh}^c + x_{hf}^c\right) n_h^c + \left(x_{ff}^c + x_{fh}^c\right) n_f^c\right] \varepsilon_c \text{ and } E^d = \left[\left(x_{hh}^d + x_{hf}^d\right) n_h^d + \left(x_{ff}^d + x_{fh}^d\right) n_f^c\right] \varepsilon_d$$

[15] Indeed, $E_i^c - E_i^d = -l\frac{t\varepsilon^c - t\varepsilon^d + m^c - m^d}{\beta} < 0$ iff $t < \bar{t}$.

yielding a global level of pollution given by:

$$E^c + E^d = \left[E_h^c n_h^c + E_f^c n_f^c\right]\varepsilon_c + \left[E_h^d n_h^d + E_f^d n_f^d\right]\varepsilon_d$$

We can state the following:

Proposition 1. *In the short run, when the locations of firms are fixed, the global carbon tax reduces global emissions through its negative impact on firm margins.*

Pollution is shaped by the spatial distribution of firms across the two countries, i.e., n_i^k $i = h, f$, marking the role of agglomeration forces on pollution regardless of the type of firm. Importantly, polluting is also affected by the spatial selection of firms, n_h^c vs. n_h^d and n_f^c vs n_f^d, namely how many dirty vs. clean firms are located in the large or in the small country. It is readily verifiable that in the short run the impact of agglomeration on total emissions is a priori ambiguous. For given individual emissions, a higher number of firms located in H, n_h, increases total pollution because firms in H always produce more than those located in F, whatever their type. However, n_h also reduces the individual emissions of each type of firm (without impacting the difference in individual emissions across countries $E_h^k - E_f^k$) because competition becomes fiercer in the country with a market size advantage. Interestingly, it is easily verified that the former effect dominates, and finally, that the agglomeration of firms in country H always increases global emissions.

This is not all. While the overall spatial distribution of firms matters for total pollution, the responsiveness of individual emissions to the spatial distribution of firms depends on the type of firm that agglomerates in the large country, dirty or clean. Because the majority of firms are dirty (i.e., $\mu > 1/2$) we find that $dE_i^k/dn_h^d < dE_i^k/dn_h^c < 0$. In other words, individual emissions fall more rapidly with the concentration of dirty firms.

We turn now to the long-run analysis to define the stable spatial distribution of firms, namely, long-run location equilibria.

4 Long-run analysis − Mobile firms

The long-run equilibrium is characterized by the endogenous decision of heterogeneous firms regarding where to locate. This implies spatial distributions of each k-type firm in the two countries such that no individuals can earn a higher return to capital by investing in the other country and no firm has an incentive to relocate.[16] *A priori*, many different types of spatial configuration may exist, characterized by very different levels of global pollution. For instance, all firms − dirty and clean − may *co-agglomerate* in one country and serve the other via exports. It might also be that *only dirty firms agglomerate* in one country whereas clean firms are dispersed, or vice versa, *only clean firms agglomerate* whereas dirty ones are dispersed. Finally, we could observe a *perfect selection* of all clean firms agglomerated in one country and all dirty firms in the other.

[16] Following Okubo et al. (2010), we assume that individuals decide in which country to invest their capital while the allocation of capital across types of firms (clean or dirty) remains exogenous. This can be explained by assuming that firms learn about their marginal cost level only after the location of the investment has been decided. Once individuals know the type of firm in which their capital was invested, they perfectly anticipate the short-run equilibrium and choose to invest their capital in the most profitable country.

Denote by s_k the *share* of k-type firms located in the large country H such that the number of firms in H can be written as $n_h = \mu n s_d + (1-\mu) n s_c$ where $(1-\mu)s_c n$ and $\mu s_d n$ represent the number of clean and dirty firms in country H, respectively. For readability, a spatial location is given by the share of clean s_c and dirty firms s_d located in country H. For instance, $(s_c, s_d) = (1,1)$ stands for the location equilibrium with co-agglomeration of all clean and dirty firms in the large country – country H . Clearly, defining the share of firms located in H, automatically defines the share of firms in F.

In this section, we first determine location equilibria. Then, we study the effect of the global carbon tax on the type of location equilibria that arise. Finally, we turn to the pollution analysis of the carbon tax in the long run.

4.1 Long-run location equilibria

The return to capital invested in a k-type firm is determined by the zero-profit condition. Using (6) and (7), we obtain:

$$r_h^k = \frac{\lambda l}{\beta}\left(p_h^* - m^k - t\varepsilon^k\right)^2 + \frac{(1-\lambda)l}{\beta}\left(p_f^* - m^k - t\varepsilon^k - \tau\right)^2$$

and

$$r_f^k = \frac{\lambda l}{\beta}\left(p_h^* - m^k - t\varepsilon^k - \tau\right)^2 + \frac{(1-\lambda)l}{\beta}\left(p_f^* - m^k - t\varepsilon^k\right)^2$$

when the firm is located in country h and in country f, respectively. The difference in the return to capital for a k-type firm between country H and F is:

$$\Delta r^k(n_h) = \frac{l\tau}{\beta(n+1)}\left[(n - 2\lambda - 2n_h + 1)\tau + 2(2\lambda - 1)\left(a + n\omega - (n+1)\left(t\varepsilon^k + m^k\right)\right)\right] \tag{11}$$

where $n - 2\lambda - 2n_h + 1$ is proved negative in Appendix 1 and the term $a + n\omega - (n+1)\left(t\varepsilon^k + m^k\right)$ is positive for all positive values of τ_{trade} and for all types of firm. In addition, we verify that the carbon tax reduces the spatial gap in the return to capital and therefore may act as a dispersion force (see Appendix 2).

Using (11), we can immediately rule out two types of location equilibria: co-agglomeration in the small country and any location with the partial concentration of each type of firm in a country. In fact, note that

$$\Delta r^c - \Delta r^d = \frac{2l\tau(2\lambda - 1)}{\beta}\left(t\left(\varepsilon^d - \varepsilon^c\right) + m^d - m^c\right) \tag{12}$$

This expression is always negative for $t < \bar{t}$. Therefore, the long-run equilibrium location of firms cannot involve a location that corresponds to $\Delta r^c = \Delta r^d = 0$ with $0 < s_k < 1$ for each k-type firm. In addition, for $n_h = 0$, we have $\Delta r^k > 0$ for each k-type of firm, implying that both dirty and clean firms have an incentive to move to the large country and never co-agglomerate in the small one. Hence, there are only four *candidate* equilibrium locations: i) *co-agglomeration* in country H, which we denote as $(s^c, s^d) = (1,1)$ if $\Delta r^c > \Delta r^d > 0$; ii) *agglomeration of only dirty firms* in the large country H and dispersed clean firms, $(0 < s_c < 1$ and $s_d = 1)$, if $\Delta r^c = 0 < \Delta r^d$; iii) *perfect selection* with clean firms agglomerated in F and dirty firms agglomerated in H, $(s_c = 0$ and $s_d = 1)$, if $\Delta r^c < 0 < \Delta r^d$; iv) *only full agglomeration of clean firms* in the small country F and the dispersion of dirty ones, $(s_c = 0$ and $0 < s_d < 1)$, if $\Delta r^d = 0 < \Delta r^c$.

Define $\tilde{s}_c^t$ and $\tilde{s}_d^t$, as the share of clean and dirty firms in the large economy that correspond to the solutions $\Delta r^c\left(s^c, s^d = 1\right) = 0$ and $\Delta r^c\left(s_c = 0, s^d\right) = 0$, respectively:

$$\tilde{s}_c^t \equiv \tilde{s}_c - \frac{t\,(2\lambda - 1)}{n\tau\,(1-\mu)}\left(\varepsilon_c + n\mu\left(\varepsilon_c - \varepsilon_d\right)\right) \text{ and } \tilde{s}_d^t \equiv \tilde{s}_d - \frac{t\,(2\lambda-1)}{n\tau\mu}\left(\varepsilon_d + n\left(\varepsilon_d - \varepsilon_c\right)(1-\mu)\right)$$

where

$$\tilde{s}_c \equiv \frac{1}{2}\frac{2\mu - 1}{\mu - 1} + \frac{(2\lambda - 1)}{2n\tau\,(1-\mu)}\left(2a - 2m^c - 2n\mu\left(m^c - m^d\right) - \tau\right) \tag{13}$$

and

$$\tilde{s}_d \equiv \frac{1}{2\mu} + \frac{1}{2}\frac{(2\lambda - 1)}{n\tau\mu}\left(2a - 2m^d + 2n\,(1-\mu)\left(m^c - m^d\right) - \tau\right) \tag{14}$$

It is readily verified that the share of clean and dirty firms located in H is a decreasing function of the level of trade costs τ. Thus, it remains to check which ranges of trade costs allow the above four possible spatial configurations to emerge. Given (11), by solving $\Delta r^c = 0$ for τ, at the *co-agglomeration* equilibrium, we obtain the trade cost value $\tau_a\,(t)$. Similarly, by solving $\Delta r^c = 0$, for τ, at *perfect selection*, we obtain the trade cost value $\tau_c(t)$ and by solving $\Delta r^d = 0$ at the *full agglomeration of clean firms* we find $\tau_d(t)$. For readability, these thresholds are detailed in Appendix 3 where we also we show that $\tau_d(t) > \tau_c(t) > \tau_a\,(t) > 0$ and $d\tau_d\,(t)\,/dt < d\tau_c\,(t)\,/dt < d\tau_a\,(t)\,/dt < 0$ for any $t < \bar{t}$.

So far, abstracting for the trade condition ensuring that firms undertake exporting activities, two comments are in order. First, the spatial configuration arises as a consequence of the balance between the competition and market size effects, moderated by the trade cost level. The smaller the trade costs, the more convenient it is to export rather than to locate in the small economy, to take advantage of the apparent market size of country H. Furthermore, the smaller the trade costs, the smaller is the shield from the competition obtained by relocating. Accordingly, *the market size effect dominates the competition effect and co-agglomeration in H is the equilibrium location corresponding to the lowest possible range of trade costs* $(0; \tau_a(t))$. As the trade costs increase above $\tau_a(t)$, some of the less productive firms - some clean ones - leave the large country to escape competition, whereas all dirty firms remain in H. When the trade costs are even higher than $\tau_c(t)$, all clean firms leave the large country as now the trade costs are a shield against the competition. Finally, when the trade costs are relatively high and reach $\tau_d(t)$, some of the dirty firms join the clean firms in the small country to soften competition, so clean firms remain agglomerated in the small country whereas the dirty ones are dispersed across the two countries. Second, each one of these trade-cost thresholds decreases with the carbon tax. Hence, the higher the carbon tax, the lower is the trade-cost threshold that triggers the shift from one spatial configuration to the other. *Accordingly, a rise in the carbon tax distorts the potential spatial configurations by enlarging the range of trade costs that favor the emergence of the most dispersed spatial configurations, provided that this range of trade costs is compatible with the trade condition.*

This is not the end of the story, and the effects of a carbon tax are even more subtle. The level of carbon tax may render the trade condition making the profitability of exporting firms more stringent, rendering international trade less convenient. We show that the carbon tax exerts a stronger reducing effect on the trade threshold than on trade-cost thresholds, triggering the shift from one spatial equilibrium to the other (i.e., $d\tau_{trade}/dt < d\tau_d\,(t)\,/dt < d\tau_c\,(t)\,/dt < d\tau_a\,(t)\,/dt$). In addition, we verify that under the extreme assumption of a zero carbon tax we have $\tau_{trade}(t=0) > \tau_d(t=0)$. Therefore, whether or not the trade condition keeps being higher than trade cost threshold values that trigger the shift from one spatial configuration to the other ultimately depends on the level of the carbon tax.

Let us denote by t_1, t_2, and t_3 carbon tax values such that, respectively, $\tau_{trade}(t_1) = \tau_d(t_1)$, $\tau_{trade}(t_2) = \tau_c(t_2)$ and $\tau_{trade}(t_3) = \tau_a(t_3)$. We show that the global carbon tax interplays with the market size asymmetry to define the following location equilibria of exporting firms:

Proposition 2. *Under the condition that firms do engage in international trade, the long-run location equilibria are as follows:*

(i) all location equilibria $(1,1)$, $(\tilde{s}_c^t, 1)$, $(0,1)$, $(0, \tilde{s}_d^t)$ *emerge if* $\lambda < \lambda_1$ *or if* $\lambda > \lambda_1$ *and* $t < t_1$*;*

(ii) location equilibria $(1,1)$, $(\tilde{s}_c^t, 1)$, $(0,1)$ *emerge if* $\lambda > \lambda_1$ *and* $t_1 < t < t_2$*;*

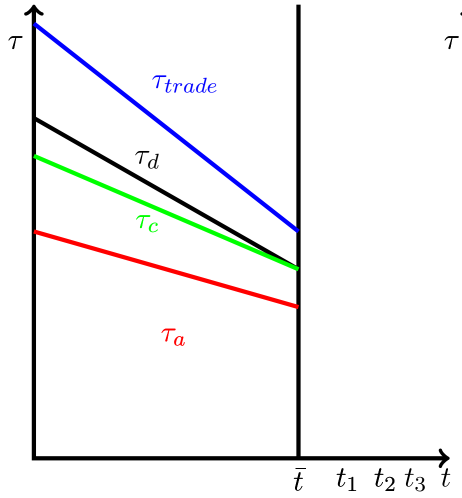
(iii) location equilibria $(1,1)$, $(\tilde{s}_c^t, 1)$ *emerge if* $\lambda_2 > \lambda > \lambda_1$ *and* $t > t_2$ *or* $\lambda > \lambda_2$ *and* $t_3 > t > t_2$*;*

(iv) only the location equilibrium $(1,1)$ *emerges if* $\lambda > \lambda_2$ *and* $t > t_3$.

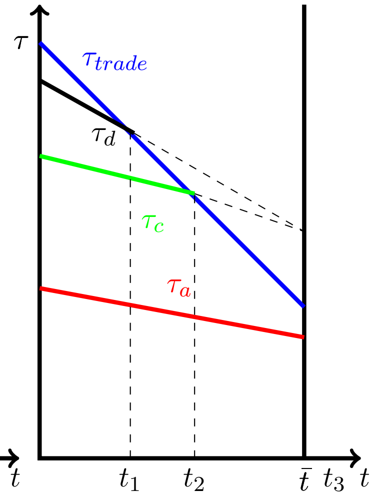
Proof. See Appendix 4. □

The aforementioned proposition states that depending on the magnitude of the market size asymmetry, a global carbon tax might influence the *type* of location equilibria that emerge (i.e. $(1,1)$, $(\tilde{s}_c^t, 1)$, $(0,1)$, or $(0, \tilde{s}_d^t)$). When the market size asymmetry is limited (that is, $\lambda < \lambda_1$) or when the carbon tax is low enough (that is, $t < t_1$), all types of location equilibria are compatible with the trade condition. In contrast, when the market size asymmetry is higher than λ_1, the most dispersed location equilibria can be eliminated by the introduction of the carbon tax. This happens for $(0, \tilde{s}_d^t)$ as soon as $\lambda > \lambda_1$ and $t > t_{1.}$ In addition, the spatial equilibrium $(0;1)$ is eliminated as soon as $\lambda > \lambda_2$ and $t > t_2$, and the location equilibrium $(\tilde{s}_c^t, 1)$ is also eliminated for all $\lambda > \lambda_2$ and $t > t_{3.}$ We call this the *no-trade effect*, which occurs when $t > t_1$ (i.e., $\tau^d(t) > \tau_{trade}$), $t > t_2$ (i.e., $\tau^c(t) > \tau_{trade}$), or $t > t_3$ (i.e., $\tau^a(t) > \tau^c_{trade}$) as long as the market size asymmetry is high (λ higher than λ_1 or λ_2). This result can be explained by the impact of the carbon tax on location forces. When the market size asymmetry is important, country H becomes more attractive but fiercer competition in that country lowers the local price. Exporting to this country remains profitable if and only if the carbon tax is low enough to preserve firms' margins on the foreign market. Otherwise, firms might relocate to the larger country to restore the margin on their foreign sales, thanks to the higher price level in country F.

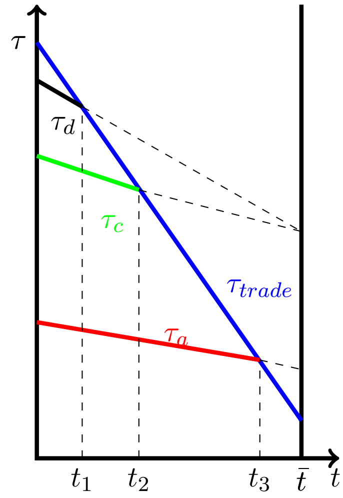
Figure 1 illustrates the selection of location equilibria according to the size asymmetry between countries. In panel (a), all location equilibria with trade are possible, whereas when the size asymmetry and carbon tax increase (panels (b) and (c)), the most dispersed location equilibria cannot emerge in the presence of trade. Indeed, we observe that when the market size advantage of country H increases above λ_1 (panel b), the τ_{trade} curve crosses trade thresholds curves τ^d and τ^c. And when the market size advantage of country H further increases above λ_2 (panel (c)), the τ_{trade} curve also crosses trade threshold curve τ^a. This implies, for example when $\lambda_1 > \lambda > \lambda_2$, that location equilibrium $(0, \tilde{s}_d^t)$ remains compatible with the trade condition if and only if the carbon tax is lower than t_1.



(a) $1/2 < \lambda < \lambda_1$



(b) $\lambda_1 < \lambda < \lambda_2$



(c) $\lambda_1 < \lambda_2 < \lambda$

Figure 1: The selection of location equilibria compatible with the trade condition

In addition, the carbon tax can also affect the spatial distribution of firms, *at the margin*, for given spatial configurations characterized by the partial agglomeration of firms $(0, \tilde{s}_d^t)$ and $(\tilde{s}_d^t, 1)$. In this case, a marginal rise in the global carbon tax reduces the share of firms located in country H. This is due to the fact that the carbon tax reduces firm output through the decline in their margin, and this effect is proportional to the market size of the country in which the good is sold.

Hence, the level of carbon tax may crucially affect the set of possible location equilibria and, in turn, the level of emissions. We summarize these results as follows.

Proposition 3. *If markets are strongly asymmetric* ($\lambda > \lambda_1$), *as the global carbon tax increases, the spatial configuration becomes more and more agglomerated. Otherwise, when markets are more similar, a rise in the global carbon tax increases dispersion for spatial configurations characterized by partial agglomeration of one type of firm.*

As discussed in Section 3, these results have relevant repercussions for the level of pollution in both countries because the concentration or dispersion of firms leads to striking differences in emission levels. We analyze the level of pollution corresponding to each location equilibrium in the next section.

4.2 Pollution in the long run

We turn now to the environmental effects of the implementation of a global carbon tax. Denote by $\boldsymbol{E}^t(1,1)$, $\boldsymbol{E}^t(\tilde{s}_c, 1)$, $\boldsymbol{E}^t(0,1)$, and $\boldsymbol{E}^t(0, \tilde{s}_d)$ the level of global emissions for each location equilibrium. To address this issue, we start with co-agglomeration in the large country $(1,1)$ and , perfect selection $(0,1)$:

$$\boldsymbol{E}^t(1,1) = \boldsymbol{E}(1,1) - t\Lambda \text{ and } \boldsymbol{E}^t(0,1) = \boldsymbol{E}(0,1) - t\Lambda \tag{15}$$

$$\text{with } \Lambda = \frac{nl}{\beta(n+1)}\left(\mu(\varepsilon_d - \varepsilon_c)(\varepsilon_c + \varepsilon_d + n(\varepsilon_d - \varepsilon_c)(1-\mu)) + \varepsilon_c^2\right),$$

where $\boldsymbol{E}(1,1)$ and $\boldsymbol{E}(0,1)$ are expressions not depending on t and defined in Appendix 5. We check that Λ is positive under assumption (9), such that the *carbon tax reduces the global level of emissions*. Regarding these two spatial configurations, the reduction in emissions is exclusively driven by the adjustment of the individual output of each type of firm (because $\tilde{s}_d^t$ and $\tilde{s}_c^t$ are constant). This *Pigouvian effect* amounts to $t\Lambda$.

Turning to the two other location equilibria where at least one type of firm is dispersed, we have

$$\boldsymbol{E}^t\left(\tilde{s}_c^t, 1\right) = \boldsymbol{E}\left(\tilde{s}_c, 1\right) - t\left(\Lambda + \Upsilon\right) \text{ and } \boldsymbol{E}^t\left(0, \tilde{s}_d^t\right) = \boldsymbol{E}\left(0, \tilde{s}_d\right) - t\left(\Lambda + \Theta\right) \tag{16}$$

$$\text{with } \Upsilon = \frac{l\left(2\lambda - 1\right)^2}{\beta\left(n+1\right)}\left(\varepsilon_c + n\mu\left(\varepsilon_c - \varepsilon_d\right)\right)^2 \text{ and } \Theta = \frac{l\left(2\lambda - 1\right)^2}{\beta\left(n+1\right)}\left(\varepsilon_d + n\left(\varepsilon_d - \varepsilon_c\right)\left(1-\mu\right)\right)^2,$$

where $\boldsymbol{E}\left(\tilde{s}_c, 1\right)$ and $\boldsymbol{E}\left(0, \tilde{s}_d\right)$ are expressions not depending on the tax t; these are defined in Appendix 5. Again, the implementation of a carbon tax clearly reduces emissions. However, it does so through both a *Pigouvian effect* (captured by Λ) and a *relocation effect* (captured by Υ and Θ). Indeed, recall that $\tilde{s}_c^t$ and $\tilde{s}_d^t$ decline with t because the carbon tax reduces the spatial difference in returns to capital (through its negative impact on the difference in net marginal cost between dirty and clean firms). Therefore, a global carbon tax reduces the spatial concentration of clean and dirty firms in the larger country. Importantly, this *relocation effect* is stronger in the spatial configuration with a partial concentration of dirty firms ($\Theta > \Upsilon$) because the carbon tax exerts a stronger effect on these firms' margins than on those of clean firms.

Finally, we compare the four location equilibria. To do this, assume for the time being that the market size asymmetry is limited ($\lambda < \lambda_1$) and, thus, bilateral trade flows may be observed under all four spatial configurations. We can rank global emissions along the equilibrium path of spatial configurations as follows:

$$\boldsymbol{E}^t\left(1,1\right) > \boldsymbol{E}^t\left(\tilde{s}_c, 1\right) > \boldsymbol{E}^t\left(0,1\right) > \boldsymbol{E}^t\left(0, \tilde{s}_d\right).$$

Trade liberalization favors agglomeration in the larger country, which is also the most polluting spatial configuration, suggesting that *trade liberalization is detrimental to the environment*. Two effects underlie this specific path of pollution. First, for a given spatial pattern, trade liberalization boosts the output per firm and thereby the level of emissions. Second, trade liberalization pushes for relocation from the smaller to the larger country because of the attractiveness of its market size. Because the average scale of production is higher in this country, such relocations amplify emissions. Interestingly, the two effects are at work in configurations (i) and (iii), leading to a more intense increase in the level of pollution. In contrast, only the quantity effect occurs in configurations (ii) and (iv), leading to a less accentuated increase in the level of pollution.

These effects are illustrated in Figure 2, representing total emissions as a function of trade costs in the absence (black line) and in the presence of a global carbon tax (green line) when $\lambda_1 < \lambda < \lambda_2$ and $t_1 < t < t_2$.

The function representing total emissions in each configuration is shifted down in the presence of a carbon tax, and global emissions remain the lowest when trade costs are the highest. In addition, note that the magnitude of the decrease in emissions strongly depends on the initial spatial equilibrium (and

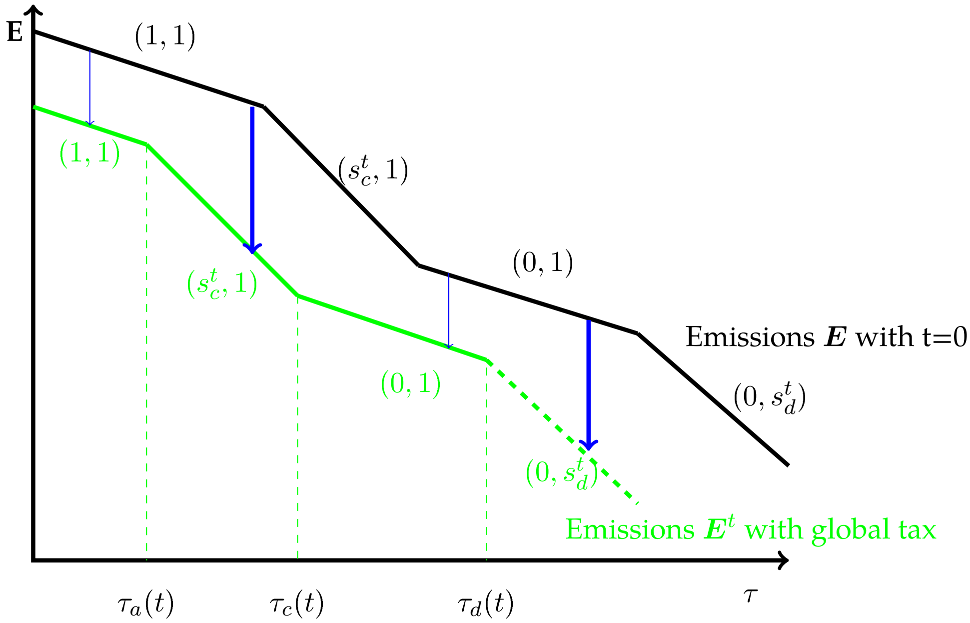


Figure 2: Global emissions $\boldsymbol{E}$ and $\boldsymbol{E}^t$ when $\lambda_1 < \lambda < \lambda_2$ and $t_1 < t < t_2$

thus on the level of trade costs) and whether this spatial pattern is stable to the introduction of the carbon tax. Taxing emissions affects the threshold levels of trade costs that allow location equilibria to arise. As a consequence, certain initial spatial configurations become unstable and some firms may relocate to country F to keep their profitability unchanged. This is the *relocation effect* that arises when the trade cost is smaller than τ_d. It can be observed that this effect is large, and thus it amplifies the efficiency of the carbon tax, when the spatial pattern shifts from *co-agglomeration* $(1, 1)$ or *perfect selection* $(0, 1)$ to a pattern that combines *partial selection* for one type of firm and *agglomeration* for the other ($(s_c, 1)$ or $(0, s_d)$). For these two configurations, *Pigouvian* and *relocation effects* accumulate and reinforce the effect of the tax on pollution (represented by the thick blue lines).

For example, consider the shift from $(1, 1)$ to $(s_c, 1)$. The relocation of some clean firms to the smaller market has two consequences. First, the new spatial distribution of clean firms is more environmentally friendly because $dE_c^t/ds_c > 0$. Second, the most polluting firms, fully concentrated in the larger market, face less competition in this market and thereby produce and pollute more ($dE_d^t/ds_c < 0$). Put differently, the effect on the environment is positive for clean firms, whereas it is negative for dirty ones. It is straightforward to check that $\left|dE_c^t/ds_c\right| > \left|dE_d^t/ds_c\right|$ for all $n < \varepsilon_c/\varepsilon_d - \varepsilon_c$ such that the positive effect dominates. For the same reasons, pollution strongly declines within the range $(\tau_d(t), \tau_d)$: the relocation of some dirty firms from the larger to the smaller market increases pollution from clean firms but decreases pollution from dirty ones to a larger extent.

These elements suggest that the efficiency of a global carbon tax to curb emissions is closely related to both the initial spatial equilibrium (and therefore the trade cost levels) and the level at which the tax is set. The following proposition summarizes our results:

Proposition 4. *Assume that the market size asymmetry is limited and trade costs are such that co-agglomeration*

$(1,1)$ or perfect selection $(0,1)$ is the initial spatial equilibrium.A global carbon tax will have a maximum reducing effect on pollution if it gives rise to relocation from the larger market to the smaller one.

The impact of the carbon tax on pollution is different when we consider a market size asymmetry higher than λ_1. As Proposition 2 states, some spatial configurations may no longer arise as location equilibria. Indeed, relatively high tax pressure might exclude some spatial equilibria because trade becomes unprofitable. If the carbon tax exceeds the threshold value t_1, the level of emissions may be the result of three effects: the Pigouvian effect and (possibly) the relocation and no-trade effects. If the last effect prevails, then one or more location equilibria disappear (represented with the green dashed line in Figure 2).

It is worth stressing that the third effect concerns the most environmentally friendly configurations. As stated by Proposition 2, scenario (iv) will no longer be among the set of location equilibria for this level of carbon tax. Thus, the pollution curves appear as shown in Figure 2. We summarize our results in the following proposition.

Proposition 5. *Assume a sufficiently high size asymmetry between countries. A relatively small global carbon tax, $t \leqslant t_1$, decreases the total level of pollution through a Pigouvian effect and, possibly, a relocation effect, leaving all spatial configurations to arise as equilibrium locations. Under a sufficiently high level of the global carbon tax, $t > t_1$, the tax makes trade inconvenient, favoring agglomeration and pollution.*

To conclude, we show that a global carbon tax induces several effects on the environment: a positive *Pigouvian effect*, a positive *relocation effect* and a negative *no-trade effect*. As long as the carbon tax does not exceed a threshold value (namely, t_1), the policy has only positive effects for the environment. It lowers emissions in any spatial configuration and may induce environmentally friendly spatial relocations. Nonetheless, there exists a threshold value, i.e., t_1, above which the effects of taxation are more complex because the set of candidate equilibria is modified. Paradoxically, the most environmentally friendly spatial configurations can be removed for global tax rates that exceed the aforementioned threshold.

5 Extensions

In our benchmark scenario, clean firms bear a higher marginal cost $m^c > m^d$ and their tax-inclusive marginal cost is also higher because the global carbon tax is assumed to be lower than the threshold $\bar{t}$. In addition, this specification considers that the majority of firms are dirty. In what follows, we relax these assumptions and show that the *relocation effect* and the *no-trade effect* of the carbon tax remain valid.

Dirty firms are more productive but bear a higher tax-inclusive marginal cost If the carbon tax reaches and exceeds $\bar{t}$, then the clean firms now enjoy the lowest tax-inclusive marginal cost and the spatial difference in return to capital between the large and the small country, according to eq. (12), is now higher for clean firms (that is, $\Delta r^c > \Delta r^d$). In other terms, dirty firms have less incentive to locate to the large country than clean ones and clean firms will be the first to self-select in the large country following a decline in trade costs. Because $t > \bar{t}$, the carbon tax also renders the trade condition even more binding so that the most dispersed spatial configurations $(1, 0)$, $(\tilde{s}_c^t, 0)$ are not compatible with the trade condition anymore. Therefore the *no-trade effect* is again in place. We can show that under the condition that firms do engage in international trade, co-agglomeration is always a stable location equilibrium whereas $(1, s_d^t)$ is compatible with the trade condition if the market size asymmetry is high or if the carbon tax does not reach a given threshold. Finally, we verify that the *relocation effect* is at work, that is, $ds_d^t/dt < 0$.

Dirty firms are less productive than clean firms One can also wonder what the impact of the global tax would be under the assumption that dirty firms bear a higher marginal cost (that is, $m^d > m^c$). In this case, dirty firms bear the highest after-tax marginal cost whatever the level of the carbon tax. This scenario is the most propitious to the spatial selection of firms as it widens the gap between the spatial difference in the return to capital of clean firms and that of dirty firms $(\Delta r^c - \Delta r^d)$.[17] In addition, this scenario is more favorable to dispersed spatial equilibria because it is compatible with any positive but small value of carbon tax. Apart from these particularities, the main mechanisms are still at work. We can show that the long run location equilibria of exporting firms are $(1, 1)$, $(1, \tilde{s}_d^t)$, $(1, 0)$, $(\tilde{s}_c^t, 0)$ if the carbon tax remains lower than a given threshold whereas only $(1, 1)$, $(1, \tilde{s}_d^t)$, $(0, 1)$ emerge if it is higher than this threshold. Finally, we verify that the *relocation effect* is at work for location equilibria characterized by the dispersion of one type of firm ($d\tilde{s}_k^t/dt < 0$ for all k).

The majority of firms are clean The distribution of firms *across types* can influence the spatial configuration through its impact on the intensity of competition (see Okubo et al., 2010). When dirty firms bearing the lowest tax-inclusive marginal cost are more numerous, the intensity of competition on the goods market is limited, allowing clean firms to agglomerate either in the small or in the large country, depending on the level of trade cost and carbon tax. Now let us consider instead that dirty firms are the minority, i.e., $\mu < 1/2$. Then the expression $(n - 2\lambda - 2n_h + 1)$ in the spatial difference in return to capital (12) can take positive or negative values depending on the spatial configuration. If $(n - 2\lambda - 2n_h + 1) > 0$ around a given spatial configuration, then $\Delta r^k > 0$ for all τ and for all k at this spatial equilibrium, meaning that co-agglomeration is the only possible spatial equilibrium. We show that this occurs when $\mu < \frac{1}{2}$ and $\lambda > \lambda^* = \frac{1}{2} + \frac{n}{2}(1 - 2\mu)$ for the spatial equilibrium characterized by $(0; 1)$, meaning that $s_c = 0$ cannot be a spatial equilibrium. Therefore, the restriction of μ reduces the number of spatial configurations compatible with the trade condition. Nevertheless, this does not change our main findings regarding the impact of the carbon tax on global emissions.

6 Conclusion

As previously documented (Wu et al., 2016), the spatial concentration of firms, productivity, and pollution vary greatly across industries. In this paper, we do not take a normative view to question what is the optimal spatial selection of firms. We rather acknowledge that at the stage of globalization we encounter

[17] Recall that $\Delta r^c - \Delta r^d$ (as expressed by eq. 12) is negative in our benchmark case with $m_c > m_d$ and $t < \bar{t}$. The expression $\Delta r^c - \Delta r^d$ becomes positive when we consider an alternative scenario where $m_c > m_d$ and $t < \bar{t}$. If we assume that $m_c < m_d$, the expression $\Delta r^c - \Delta r^d$ becomes even higher.

today, firms are not only heterogeneous with respect to the pollution they produce but they are also mobile, engage in international trade, and decide where to locate among countries with markets of different sizes. It is then of paramount importance to consider all of these features when asking whether a global carbon tax overcomes all preexisting heterogeneities and reduces pollution via a Pigouvian effect. This is the question we aimed to answer in this paper. We uncover the ability of a fully harmonized carbon tax to curb carbon emissions in a globalized economy characterized by heterogeneous countries and firms that are mobile and engage in international trade. Our results challenge the claim that a global carbon tax could succeed in improving the quality of the environment without raising competitiveness concerns.

We first show that regardless of its level, a global carbon tax might encourage some firms to relocate their activities. Importantly, the level of the carbon tax matters for the direction of the relocation and its impact on global emissions. When the carbon tax is low enough, firms relocate to the smaller country and reduce their output. In addition to the Pigouvian effect of the carbon tax, this relocation reduces global emissions by promoting a less concentrated spatial distribution of activities. Interestingly, this relocation strategy never involves clean and dirty firms at the same time. Specifically, low-cost firms relocate to the smaller country at an earlier stage of trade liberalization than high-cost firms do. Indeed, because they suffer a higher post-tax marginal cost, the latter are both less attracted to the large country and more sensitive to the higher competition within this country. If the carbon tax is too high, however, then profitability on the export market can be threatened, and firms react by relocating to the larger country to maintain their export activity. In such a case, the Pigouvian effect of the carbon tax can be counteracted by the relocation effect, giving rise to a more polluting spatial distribution of firms. Hence, despite avoiding any tax externalities, a global tax may have environmentally unfriendly effects in the long run that must be carefully taken into account.

Appendices

Appendix 1: The sign of $n - 2n_h - 2\lambda + 1$

We demonstrate that $n - 2n_h - 2\lambda + 1$ is negative in our benchmark case. A sufficient condition for $n - 2n_h - 2\lambda + 1$ to be negative for all λ is that $n - 2n_h < 0$, and thus $n_h > \frac{n}{2}$. In addition, the spatial configuration with the lowest number of firms in country H is such that $s_c = 0$ and $s_d = \tilde{s}_d$. Using expression (14), we verify that $\tilde{s}_d > 1/(2\mu)$, so that the number of firms in country H at this spatial configuration is given by $\mu\tilde{s}_d n$, which is higher than 1/2. Therefore, $n - 2n_h - 2\lambda + 1 < 0$ for all spatial equilibria.

Appendix 2: The role of firm heterogeneity

The carbon tax triggers two opposing forces on the spatial difference in return to capital that can be disentangled by examining how the net return on capital reacts to the carbon tax, namely:

$$\frac{\partial \Delta r^k}{\partial t} = \frac{2l\tau}{\beta}(2\lambda - 1)\left[\underbrace{\frac{\partial p_h}{\partial t}}_{\text{tax incidence (+)}} - \underbrace{\frac{\partial t\varepsilon_i}{\partial t}}_{\text{marginal cost (-)}}\right],\ k = c, d$$

Because of the market size asymmetry ($\lambda > 1/2$), the tax incidence effect exacerbates the difference in returns to capital across countries, whereas the impact of the carbon tax on the marginal cost has the opposite sign. The net impact is always negative for dirty firms, whose tax burden is raised by their high emissions. It is also the case for clean firms as long as the effect on the marginal cost dominates that on the tax incidence, as we assumed in (9). Consequently, we have $\frac{\partial \Delta r^k}{\partial t} < 0$ for all k and the global carbon tax erodes the benefit of being in the large country more for the dirty firms than for the clean ones :

$$\frac{d\Delta r^d}{dt} - \frac{d\Delta r^c}{dt} = -2l\tau \left(\varepsilon^d - \varepsilon^c\right) \frac{2\lambda - 1}{\beta} < 0.$$

Hence, *when different market sizes are considered, a global carbon tax is not a spatially neutral policy instrument*. Because the tax amount paid is proportional to the individual output (the carbon tax is a quantity tax), the location in the large market becomes more costly and some firms may relocate towards the small one with the aim of reducing the tax burden. Consequently, the introduction of such taxation increases the attractiveness of the small country. While this mechanism takes place in the presence of homogeneous technologies (Exbrayat et al, 2013), the existence of firm heterogeneity in terms of emission intensity matters for the magnitude of this effect. This dispersing force is stronger for dirty firms, whatever their proportion in the economy. Therefore the carbon tax can influence not only the overall distribution of firms across countries but also their distribution across types within each country.

Appendix 3: Trade thresholds

Here we define all trade cost thresholds triggering the shift from one location equilibrium to the other, in the benchmark case. Define $\tau_a(t)$, $\tau_c(t)$ and $\tau_d(t)$:

$$\tau_a(t) \equiv \tau_a - tA_a; \tau_c(t) \equiv \tau_c - tA_c; \tau_d(t) \equiv \tau_d - tA_d$$

with

$$\begin{aligned}
\tau_a &= 2(2\lambda - 1) \frac{a - m^c - n\mu\left(m^c - m^d\right)}{n + 2\lambda - 1}, \\
\tau_c &\equiv 2(2\lambda - 1) \frac{a - m^c - n\mu\left(m^c - m^d\right)}{n(2\mu - 1) + 2\lambda - 1}, \\
\tau_d &\equiv 2(2\lambda - 1) \frac{a - m^d + n\left(m^c - m^d\right)(1 - \mu)}{n(2\mu - 1) + 2\lambda - 1},
\end{aligned}$$

and

$$\begin{aligned}
A_a &\equiv 2(2\lambda - 1) \frac{\varepsilon^c + n\mu\left(\varepsilon^c - \varepsilon^d\right)}{n + 2\lambda - 1} \\
A_c &\equiv 2(2\lambda - 1) \frac{\varepsilon^c + n\mu\left(\varepsilon^c - \varepsilon^d\right)}{n(2\mu - 1) + 2\lambda - 1} \\
A_d &\equiv 2(2\lambda - 1) \frac{\varepsilon^d + n\left(\varepsilon^d - \varepsilon^c\right)(1 - \mu)}{n(2\mu - 1) + 2\lambda - 1}
\end{aligned}$$

We can easily check that $A_d > A_c > A_a > 0$ and $\tau_d(t) > \tau_c(t) > \tau_a(t) > 0$ under the assumption that $\tau_{trade} > 0$.

6.1 Appendix 4: Proof of Proposition 2

To show which are the equilibrium spatial configurations, we investigate the sign of Δr^d and Δr^c in the admissible set of τ values, namely for all $\tau < \tau_{trade}$.

We know that for any $t \in [0; \bar{t})$, $\tau_d(t) > \tau_c(t) > \tau_a(t)$. These thresholds as well as the trade condition $\tau_{trade}(t)$ are monotonic decreasing functions of t. Then, to spot the location equilibria, for any t, we shall investigate the value of the trade condition for $\bar{t}$. If the trade condition at $\bar{t}$ is higher than those thresholds evaluated at $\bar{t}$, then all four spatial configurations are equilibrium location for any admissible τ and t.

First notice that at $\bar{t}$, we have

$$\tau_c(\bar{t}) = \tau_d(\bar{t}) = 2\left(2\lambda - 1\right)\frac{a\varepsilon^d - a\varepsilon^c - m^c\varepsilon^d + m^d\varepsilon^c}{\left(\varepsilon^d - \varepsilon^c\right)\left(-n + 2\lambda + 2n\mu - 1\right)}$$

while the corresponding trade condition threshold is

$$\tau_{trade}(\bar{t}) = \frac{a\varepsilon_d - a\varepsilon_c - m\varepsilon_d}{\left(n+1\right)\left(\varepsilon_d - \varepsilon_c\right)}$$

which are both positive.

Taking the difference $\tau_{trade}(\bar{t}) - \tau_d(\bar{t})$, we have

$$\tau_{trade}(\bar{t}) - \tau_c(\bar{t}) = \left(-2\left(2n+1\right)\lambda + \left(n + 2n\mu + 1\right)\right)\frac{a\varepsilon^d - a\varepsilon^c - m^c\varepsilon^d + m^d\varepsilon^c}{\left(n+1\right)\left(n\left(2\mu - 1\right) + 2\lambda - 1\right)\left(\varepsilon^d - \varepsilon^c\right)}$$

We know that $n\left(2\mu - 1\right) + 2\lambda - 1 < 0$, and $\left(a\varepsilon^d - a\varepsilon^c - m^c\varepsilon^d + m^d\varepsilon^c\right)$ is positive due to the positivity of the trade condition. Therefore, the above expression depends on the sign of $-2\left(2n+1\right)\lambda + \left(n + 2n\mu + 1\right)$. It follows that for any $t \in [0; \bar{t})$:

$$\tau_{trade}(\bar{t}) \gtrless \tau_c(\bar{t}) \text{ when } \lambda \lessgtr \frac{n + 2n\mu + 1}{2\left(2n+1\right)} = \lambda_1 \in \left[\frac{1}{2}; \frac{1}{2}\frac{3n+1}{2n+1}\right]$$

Then, the line $\tau_{trade}(t)$ intercepts once the line $\tau_d(t)$ and we call this intercept t_1, while $\tau_{trade}(t)$ intercepts once the line $\tau_c(t)$ and we call this second intercept t_2. t_1 and t_2 lie in the interval $t \in [0; \bar{t})$ if $\lambda > \lambda_1$ whereas it lies in the interval $t \in [\bar{t}; +\infty)$ otherwise.

Now taking the difference between $\tau_{trade}(\bar{t})$ and $\tau_a(\bar{t})$, we obtain:

$$\tau_{trade}(\bar{t}) - \tau_a\left(\bar{t}\right) = \left(3n - 2\lambda - 4n\lambda + 1\right)\frac{a\varepsilon^d - a\varepsilon^c - m^c\varepsilon^d + m^d\varepsilon^c}{\left(n+1\right)\left(n + 2\lambda - 1\right)\left(\varepsilon^d - \varepsilon^c\right)}$$

with $a\varepsilon^d - a\varepsilon^c - m^c\varepsilon^d + m^d\varepsilon^c > 0$ due to the positivity of $\tau_{trade}(\bar{t})$. We verify that

$$\tau^c_{trade}(\bar{t}) \gtrless \tau_a(\bar{t}) \text{ when } \lambda \lessgtr \left(3n+1\right)/\left(4n+2\right) = \lambda_2$$

with $\lambda_2 > \lambda_1$.Therefore, the curve $\tau_{trade}(t)$ intercepts once the curve $\tau_a(t)$ and we call this intercept t_3. t_3 lies in the interval $t \in [0; \bar{t})$ if $\lambda > \lambda_2$ whereas it lies in the interval $t \in [\bar{t}; +\infty)$ otherwise.

Recall that $d\tau_d\left(t\right)/dt < d\tau_c\left(t\right)/dt < d\tau_a\left(t\right)/dt < 0$. Therefore, we conclude that $t_1 < t_2 < t_3$. In addition, we verify that these threshold values of the carbon tax are a decreasing with function of the market size asymmetry, so that $\bar{t} < t_1 < t_2 < t_3$ when $\lambda < \lambda_1$, whereas $t_1 < t_2 < \bar{t} < t_3$ when $\lambda_1 < \lambda < \lambda_2$ and $\bar{t} < t_1 < t_2 < t_3$ when $\lambda_1 > \lambda_2$.

Consequently, the compatibility of spatial configurations depends on both the market size asymmetry and the level of carbon tax. When the market size asymmetry is lower than λ_1, the trade condition threshold is higher than $\tau_d(t)$ for all $t \in (0; \bar{t})$ and therefore the four scenarios arise as equilibrium locations.

When the market size asymmetry is higher than λ_1, the most dispersed spatial configurations might disappear if the carbon tax is high because the trade condition threshold can fall to a level lower than $\tau_c(t)$, $\tau_d(t)$ or $\tau_a(t)$. Specifically if $t_1 \leqslant t \leqslant t_2$, only $\tau_a(t)$ and only $\tau_c(t)$ lie in the admissible set of trade cost values, implying that configurations $(1; 1)$, $\left(\tilde{s}_c^t; 1\right)$ and $(0; 1)$ are the only equilibrium spatial configurations with exporting firms. If $t_2 \leqslant t \leqslant \min(t_3; \bar{t})$, only $\tau_a(t)$ lies in the admissible set of trade cost values, implying that configurations $(1; 1)$ and $\left(\tilde{s}_c^t; 1\right)$ are the only equilibrium spatial configuration with exporting firms. Finally if $t_3 < t < \bar{t}$, a scenario that can happen only if $\lambda > \lambda_2$, then $\tau_a(t)$ does not lie in the admissible set of trade cost values, implying that configurations $(1; 1)$ is the only equilibrium spatial configuration with exporting firms.

Appendix 5: Definition of global emissions along location equilibria

Let $\boldsymbol{E}(s_c, s_d)$ denote the world level of emissions for a given spatial distribution of clean and dirty firms (s_c, s_d) in the absence of carbon tax. This function can be expressed as follows:

$$\boldsymbol{E}(s_c, s_d) = \frac{ln}{\beta(n+1)} \left[\begin{array}{l} ((1-\mu)\varepsilon_c + \mu\varepsilon_d)\left(a - \lambda\tau + n\left(m^c(1-\mu) + m^d\mu\right)\right) \\ +(2\lambda-1)\tau(\varepsilon_c s_c(1-\mu) + \mu\varepsilon_d s_d + n\mu(s_c - s_d)(\varepsilon_c - \varepsilon_d)(1-\mu)) \\ -(n+1)\left(m^c\varepsilon_c(1-\mu) + m^d\mu\varepsilon_d\right) \end{array} \right]$$

with $s_d > s_c$ regardless of the equilibrium spatial configuration in our benchmark case. We incorporate the equilibrium values of $\tilde{s}_c$ and $\tilde{s}_d$ as defined in (13) and (14) in the above expression to obtain $\boldsymbol{E}(1,1)$; $\boldsymbol{E}(\tilde{s}_c, 1)$; $\boldsymbol{E}(0,1)$ and $\boldsymbol{E}(0, \tilde{s}_d)$, as expressed in (15) and (16).

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