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EMISSIONS, EXPORTERS AND HETEROGENEITY: ASYMMETRIC TRADE POLICY AND FIRMS' SELECTION [a]

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Abstract

This paper examines the impact of trade policy on total emissions of greenhouse gases in an emission-augmented Melitz model that accounts for heterogeneous firms and international asymmetries. Trade improves efficiency through *selection* and *share-shifting* effects on firms, and thus – if more productive firms match with cleaner technologies – symmetric trade openness can improve overall environmental quality. Yet emission technologies, economic characteristics and trade barriers are highly asymmetric across countries. This can lead to some unexpected implications of national trade policies on total carbon emissions. We find that, even in an asymmetric setting, trade openness can help reducing global emissions. However different effects act together depending on the size, productivity and emission profile of the trading partners. We then resort to a simple parameterization of the model to show the effect of different forces. Our results suggest that trade liberalization can unambiguously lower emissions if coupled with transfers of green technology.

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1. INTRODUCTION

Shifting to a green economy and curbing global emissions is a gargantuan task. Most of the carbon mitigation efforts must come from within national borders and involve difficult domestic policy choices. There is, however, an enduring interest in the role that international trade policy can play in helping or hindering the transition to a low-carbon future. This link between trade policies and emissions arises frequently in the debate, since firms subject to domestic pro-green taxes and regulation routinely decry the loss of international competitiveness that such policies may imply. This paper contributes to this discussion about the trade-environment link by modelling explicitly the problem at the firm dimension.

An impressive theoretical and empirical literature has addressed the trade-environment nexus. Two mechanism of action are often mentioned. First, there is the so-called Environmental Kuznets Curve (Grossman and Krueger, 1993), which postulates that equilibrium pollution first rises and then falls as citizens get richer. Since trade generally boosts nations' average income, the trade-green link depends upon the channel of raising national income levels. Second, is the Pollution Haven Hypothesis (Copeland and Taylor, 1995) whereby trade – by allowing nations to specialise production in their low-cost sectors – shifts pollution-intensive activities to nations with lax (and thus low cost) carbon regulation schemes. A knock-on hypothesis is that policy setting with the Pollution Haven Hypothesis in mind leads to a 'race to the bottom' on environment stringency.

These channels, however, were identified in simple, standard trade models that focused on homogenous firms for convenience, such as the 'old' trade theory (Ricardian and Heckscher-Ohlin models) and the 'new' trade theory (Brander-Krugman and Helpman-Krugman models). These theories focus on how freer trade shifts the pattern and level of global production, making them natural starting points for explorations into trade-carbon linkages. After all, pollution – especially carbon emissions – mostly relate to the aggregate level of output of various sectors. The downside, however, is that all traditional models assume away mechanisms of action that may well be important for firms, competitiveness and carbon leakages.

One set of such mechanisms are allowed for in the so-called 'new, new' trade theory, which focuses on firm heterogeneity (Melitz, 2003). Among the many features that put the extra 'new' in 'new, new' trade theory are *selection* and *share-shifting* effects. That is, freer trade lowers the bar to exporting, so more firms export. The new exporters tend to be relatively efficient since overcoming the export bar remains difficult. The selection effect happens when the stiffening of competition from foreign firms drives out the least efficient firms. Then market shares are shifted to more efficient firms, by the combination of new export sales for the best firms and the redistribution of the former sales of inefficient firms that exit the market. Importantly, both effects raise industrial productivity in ways that just could not be envisaged in the old or new trade theories. In this paper, we argue that this mechanism is important not only for productivity, but also for emissions.

Two other papers have explored the implications of heterogeneity in firms' productivity for carbon emissions. Forslid et al. (2014) use an adapted version of the Melitz model to examine new links between trade and investments in abatement technology. In their model, emission intensity is negatively related to firms' productivity and exports, because larger production scale supports more abatement investment and, in turn, lowers emissions per output. Their empirics confirm this pattern exists in Swedish firm-level data, as emissions per firm are negatively related to productivity and export status. Kreickemeier and Richter (2014) also examine the effect of trade liberalization on the quality of the environment in a heterogeneous-firms setting. They look at the reallocation effect of trade deriving from an increase in the relative size of the most productive firms, finding that even when domestic emissions decrease following unilateral liberalization, domestic pollution may rise due to the change in foreign emissions. Their model, however, does not explain the link between firms' productivity and emissions, but just assumes that a negative relationship holds in most cases.

Out paper proposes an extended emissions-augmented Melitz model and uses it to investigate the effects of trade policies on total emissions in a variety of settings. We describe the relationship between firms' productivity and emissions, as a matching process between the best firms with cleanest technologies, to avoid future costs of changing technology if environmental regulations tighten. The key contribution of our model is that it allows for important national asymmetries. We work with two nations – one of which we view as a developing nation with poor abatement technology, and the other an advanced technology nation with good abatement capacity. By allowing for size and and productivity differences, we find new channels and new interactions among the variables linking trade and emissions.

We argue that trade policies linked to cross-boundary pollution issues that are based on homogeneous firm trade theory can be misdirected. Such models focus on the *average* characteristics of a nation's industries. However, policy does not typically operate at the average, but rather on marginal firms – firms are that are near the exit margin on one hand, or the export margin on the other. To illustrate this with a simple example, consider if a foreign nation's steel mills are on average dirtier than domestic ones, but all its exporting steel mills are cleaner (because they are more productive and can better face trade costs) . In this case, a policy based on average emissions might suggest setting up a tariff against the dirty nation's steel imports. This however would not achieve the desired effect: dirty domestic firms would be protected against cleaner rivals, and world's allocation of production would not go to the cleanest firms. A worldview that focuses on firm heterogeneity, however, would suggest a pro-export policy, which would lower rather than raise emissions through selection and share-shifting effects.

The paper is structured as follows. Section 2 examines the extant literature on competitiveness effects of environmental regulation, heterogeneous firms and trade policy. Section 3 outlines the model, the key channels for policy effects and their implications for carbon emission. Section 4 considers the case of asymmetric nations that differ in size or productivity, looking also at an expanding demand or a technological catch-up. Finally, section 5 discusses other implications of the model and avenues for further research.

The key message of the paper is that the environmental effect of trade policy - like any other green regulation that affects global pollution – depends on which firms are selected, which technologies are favoured and how this changes the structure of industrial production. We find that the most effective design for trade policies so to ensure that they improve efficiency, but do not increase emissions, would be to couple trade liberalization with transfers of clean technologies.

2. BACKGROUND

The old trade and environment literature on Environmental Kuznet Curves and Pollution Havens are extensions of well know trade results and growth theories. The most recent literature, driven by new competitiveness concerns related to climate change regulation, is now more focused on the interplay among different countries. The latest research focuses particularly on policy leakages across regions with differential regulations and on competitiveness effects of environmentally friendly trade policies.[2] There exist many channels for pollution spillovers and these are particularly significant in the case of global emissions such as CO_2. Production shifting and specialization in polluting industries can occur even without firms' relocation, as a country replaces domestic production with imports with high carbon content.

This realization drove parts of the literature to focus on trade and production patterns, with firms remaining in the same location, rather than on the footloose capital of the Pollution Haven Hypothesis. [3]

This realisation drove parts. Then the literature tried to quantify the industrial 'damage' from carbon related policies and eventually the need for some trade protection. Two sets of indicators are used to measure damages of green trade policies.[4] First, carbon costs (or value at stake), which is the sum of all costs (including the indirect cost of an increase in the price of energy), since an energy-intensive firm would face a larger increase in their costs (see Ellerman et al. 2010 for the EU, Aldy and Pizer 2009 for the USA). A second measure is trade exposure, namely imports plus exports over total domestic market, or turnover.[5]

These considerations about competitiveness loss provide a rationale for governments support to national firms suffering from a competitiveness loss. The two macro-categories of unilateral, protective interventions that a country can adopt are i) output-based allocations

[2] Typically, integrated assessment models are employed to estimate these competitiveness costs (Babiker 2001, 2005, Bollen et al. 2000, Burniaux and Oliveira Martins 2000, Kuik and Gerlagh (2003), Paltsev 2001). Some of these models also account for the possibility of technology diffusion (Gerlagh and Kuik 2007). These find significant impacts especially for energy-intensive, trade-exposed industries.

[3] Ederington et al. (2005) find that pollution abatement costs are a small component of total costs, unrelated to trade flows, and industries with large abatement costs are the least geographically mobile. Similarly Levinson and Taylor (2008) 'unmask' the Pollution Haven effect looking at trade impacts of US environmental regulation. They find that other factors beyond environmental stringency are more significant for firms' choices.

[4] Other concerns for firms point are: investment options; products differentiation and market segmentation; transportation costs after the increase in the cost of carbon; customers reaction to a price increase, vertical integration of industry, quality issues, long term contracts; legal and political environment (Dröge et al. 2009).

[5] Martin et al. (2012) note that the EU has granted an extremely generous allowance scheme to compensate for carbon leakages, especially because of the trade exposure, which is not directly related to carbon.

and ii) border tax adjustments. The former consists of allocating emission permits in various ways to those firms that would be most damaged, usually based on their productivity (see Quirion 2009 for an outline the various controversies concerning the effects of these allocations). However, the welfare costs of these exemptions can be quite substantial (Böhringer and Rutherford 1997).

Border tax adjustments, on the other hand, aim at levelling the playing field for domestic firms with respect to foreign firms producing in countries with lax abatement policies. The intervention can take many forms and can be on the import side, adjusting competitiveness for domestic consumption, or on the export side, or both. Adjustments at the border are highly debated as they can be conflicting with WTO provisions (Zhang 2012). The problem of trade-related measures is the potential distortion on international markets induced by protecting local firms that would be otherwise driven out of production without the protective measures. Moreover, these distortionary policies can be deleterious for emissions, as well.

However, previous estimates of competitiveness loss and carbon leakages are based on models that ignore firm heterogeneity. It is now well known in the trade literature that firms are heterogeneous and some important effects can occur at the 'tails' of the firms' distribution. The literature on heterogeneous firms has developed exponentially in trade theory since the seminal works of Melitz (2003) – see for instance Helpman, Melitz and Yeaple (2003), Baldwin (2005) and Baldwin and Forslid (2006). Many works extended the standard framework to explore effects that can be very relevant for environmental analysis, as well. Notably, Demidova (2008) looks at the effects of technological improvements in one country, and finds that these can hurt their more advanced partners in a heterogeneous firms' framework. But the context of carbon emissions and leakages, there are still very few models looking at heterogeneous firms.

As mentioned above, Forslid et al (2014) and Kreickemeier and Richter (2014) are the only noticeable exceptions. We go beyond their work in that we look at the policy implications on aggregate emissions considering various asymmetries between countries. Thus the goal of the our paper is to build a new model that can explain the firm level emission-productivity linkage and account for the effects of various trade policies in asymmetric countries (with different pollution technologies, different size, different firms' productivities) to see the effects on total pollution emissions.

3. MODEL

3.1. Production

We begin with a baseline model akin to Melitz (2003), Helpman, Melitz and Yeaple (2003), Baldwin (2005) and Baldwin and Forslid (2006). The key addition is represented by emissions technologies, which match to firms with heterogeneous productivities. Initially we work with nations that are symmetric in all but their average emission technology. As we shall see, even in this simple scenario, the effects of trade policies are non-trivial with carbon leakage in some situations. We subsequently consider additional asymmetries such as country sizes and production technology.

The baseline model considers two nations (Home and Foreign) with identical tastes, size and production technology, interacting trough international trade. We think of Home as the developing country with initially dirtier industries. Foreign is a developed country with cleaner technologies and possibly environmental concerns on its agenda. Each country has two sectors of production: a Walrasian sector - characterized by perfect competition, constant returns to scale, and homogeneous goods - and a manufacturing sector - characterized by differentiated products, monopolistic competition à la Dixit-Stiglitz (1977) and increasing returns to scale. As usual in these models, we embrace the simplifying assumption of costless trade in the Walrasian sector and costly trade in the manufacturing sector. As is well known, this equalises Home and Foreign wages and thus cuts out wage-linked channels of endogeneity. This is useful since we believe the wage effects of green-linked trade policies are second order compared to the competitiveness and environmental impacts.

Preferences of all consumers are Cobb-Douglas with the fraction of expenditure on manufactured goods given by μ. Tastes over the Dixit-Stiglitz varieties are CES as usual. Thus:

$$U = \ln R - \ln \mathrm{P}; \quad \mathrm{P} \equiv (p_T)^{1-\mu}\left(\int_{i\in\Theta} p_i^{\,1-\sigma}\,di\right)^{\mu/(1-\sigma)} \tag{1}$$

where R is expenditure, P the price index, p_i is the price of a variety i (we choose units of the 'traditional', Walrasian good so its price equals unity, $p_T = 1$). Sigma is the elasticity of substitution among varieties, with $0 \leq \mu \leq 1 \leq \sigma$, and Θ the set of all varieties consumed.

3.2. Production

Manufacturing is characterized by a number of fixed costs. All firms pay the standard Dixit-Stiglitz fixed cost of introducing a new variety, $\boldsymbol{F_I}$ (cost of developing a 'blueprint'). Firms that decide to sell domestically must pay a 'beachhead' fixed cost of $\boldsymbol{F_D}$ to enter the home market. Firms that also export pay an additional beachhead cost of $\boldsymbol{F_X} > \boldsymbol{F_D}$. Additionally, production entails a variable (marginal) cost, $\boldsymbol{a}$. And finally, exporting goods faces an additional variable cost related to trade frictions, so it costs $\boldsymbol{\tau \cdot a}$ to sell a unit abroad; $\tau > 1$ encompasses trade barriers such as *ad valorem* tariffs, or green-linked taxes. Firms are heterogeneous in their variable costs of production, or unit labour input requirements, a. Namely, firm-i's output x_i is:

$$x_i = \frac{l_i}{a_i} \tag{2}$$

where l_i is the firm's variable-cost labour employment. Taking Home labour as numéraire, wage is unity, so a_i is the firm's marginal cost. Standard calculations show that:

$$c_i = \frac{p_i^{-\sigma} \mu R}{P^{1-\sigma}}, \quad c_i^* = \frac{p_i^{*-\sigma} \mu R}{P^{1-\sigma}} \qquad p_i^* = \frac{a_i}{1-1/\sigma}, \quad p_i^* = \frac{\tau a_i}{1-1/\sigma} \qquad \pi_i = \frac{\mu E}{\sigma} \tag{3}$$

where c, p and π are the consumption, price and operating profit of a typical variety, and the asterisk, "*", indicates foreign variables, so in this case imported-variety consumption and prices; E is total consumer expenditure on variety-i, counting both domestic and export sales (if any). Observe that the best firms (with lowest a) have lower prices, higher output and higher profits. In this paper we take R as a parameter to reduce the amount of uninformative clutter. It would be simple – but uninformative – to embed our demand structure in a quasi-linear setting where R became a taste parameter.

3.3. Emissions

A number of empirical studies that find that, generally, more productive firms are also cleaner (Batrakova and Davies 2012, Cole et al. 2005, Cole and Elliot 2008, Cui et al. 2012, Forslid et al. 2014, Holladay 2009, and Mazzanti and Zoboli 2009). There can be different explanations for the negative link between productivity and emissions.[6] Forslid et al. (2014) present a mechanism based on the idea that, since more productive firms have higher sales, they can make higher fixed cost investment in abatement, exploiting scale economies. Alternatively, we could consider other theoretical explanations for this empirical finding, even without investments in abatement. For instance this could be seen as a problem of two-ways heterogeneity matching, whereby the best firms choose to adopt heterogeneous emission-reducing technologies, in order to avoid future potential costs from environmental regulation. Even in the absence of complementarity in production, search frictions for new technologies could generate a natural reason for positive assortative matching to arise: once a firm adopts a technology, it would be costly to change for a different technology, so the most productive firms prefer to choose the best technology they can afford. This is similar to the two way assortative matching described in Shimer and Smith (2000), even if the output of the match is not shared between the two parties. Here, in order to keep it simple, we reduce the problem to one-way heterogeneity, in which we can take the most advanced technology in a given country, β, and scale it through firm's heterogeneous productivity, to get the heterogeneity in emission. Specifically:

$$e_i = a_i^{\beta} x_i \ ; \quad \beta \geq 0 \tag{4}$$

so emissions for a given firm are proportional to its output *x*, but the factor of proportionality depends on firm-level productivity (since productivity rises as '*a*' falls, more productive firms emit less per unit of *x*). The behaviour of the emissions function is determined by the emission technology parameter, β.[7] Here we do not consider the case when β<0, even if the model can easily accommodate for this, as it would imply that less productive firms are cleaner, in contradiction with the empirical evidence. A critical value of β as far as the firm-size pollution profile is concerned is when it equals σ. Even if the emission technology is positive, it could still be that, with an increase in demand, firms pollute more, since they produce more units of output. To see this, consider the pollution

[6] This relationship might vary significantly from industry to industry. Since we eschew from the industry level in our model, the country differences in the emissions-productivity nexus reflect the overall industrial composition of a country's economy.

[7] Kreickermeier and Richter note that emissions can be i) exactly proportional to labour inputs (when β = 1), or ii) independent of firm's efficiency (when β = 0).

associated with production for domestic sales. Using equation (3), emission associated with domestic sales of typical firm-*i* are:

$$e_i = a_i^{\beta} \frac{p_i^{-\sigma} \mu R}{P^{1-\sigma}} = (a_i^{\beta-\sigma}) \frac{\mu R}{(1-1/\sigma)^{-\sigma} P^{1-\sigma}} \tag{5}$$

When $\beta \geq \sigma$, emission technology can compensate the elasticity of substitution that causes more output to be produced: per firm emissions associated with consumption of variety-*i* rise with '*a*', so they are higher for less efficient firms, even accounting for the fact that less efficient firms sell less units of output. If the inequality is reversed, emissions are higher for the most efficient firms since, even if they pollute less per unit, the sell many more units than least efficient firms.[8] This is particularly important when analysing selection effects and carbon leakage arising from green-linked trade policies. In what follows, we model the developing nation (Home) as having a lower $\beta < \beta *$, so that on average Foreign firms are cleaner than Home firms.

3.4. The Pareto distribution

In order to solve analytically the model, a firm's marginal costs are assumed to be drawn randomly from a Pareto distribution[9] with cumulative density function G[a] = $(a/a_0)^k$ and support 0 ≤ a ≤ a_0 ≡ 1. The distribution of firms can be seen in Fig.1. Firms face a constant probability of death according to a Poisson process with hazard rate δ, in order to keep the present value of any firm finite. It is useful to segment the population of firms into three types. N-type firms enter by paying F_I, only to discover that they are too inefficient (i.e. their *a* is too high) to make production worthwhile, so they produce nothing. D type firms pay F_I and find that they have a productivity *a* low enough to make sinking F_D worthwhile, but not F_X, so they sell only locally. Firms with sufficiently low *a*'s sink both F_D and F_X and thus sell

[8] Consider the relative emissions of two firms $e(a_1)/e(a_2) = (a_1/a_2)^{\beta-\sigma}$: the emissions of firm 1 are smaller than those of firm 2 when firm 1 is more productive ($a_1 < a_2$), as long as the exponent is positive.

[9] The literature adopts frequently a Pareto distribution because it is tractable: any continuous portion of a Pareto distribution is itself a Pareto distribution with the same shape parameter (k), only with different upper and lower bounds (Baldwin 2005). Eaton et al. (2011 show that empirically this distribution is a valid approximation.

domestically and abroad; we call these X-types. Two endogenous thresholds, a_X and a_D, define the types as shown in Fig.1.

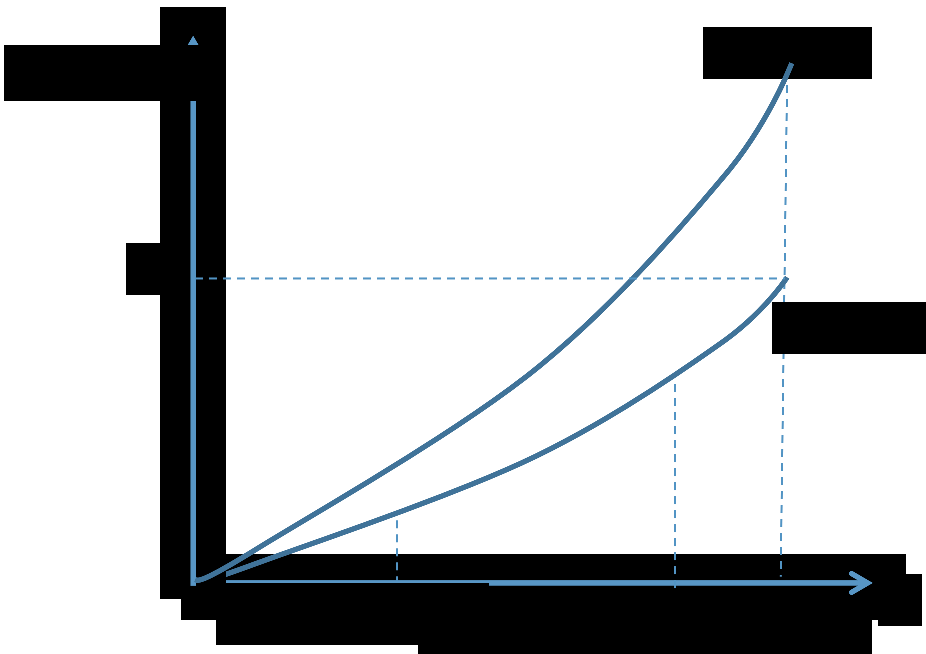

Fig.1 *– Firms' mass ordered from most efficient (left) to least efficient (right)*

3.5. Open economy equilibrium

Solving the model requires two cut-off conditions for entering the domestic and foreign market and a free entry condition that brings expected profits to zero. The two standard cut-off conditions in the Melitz model are identical in our two countries. Firms operating exactly at the D-type and X-type margins have *a's* such that operating profits just cover the fixed beachhead costs, namely:

$$\frac{a_D^{1-\sigma}}{\Delta}\mu R = f_D \qquad \phi\frac{a_X^{1-\sigma}}{\Delta}\mu R = f_X \tag{6}$$

where $f_D \equiv \sigma\delta F_D$ and $f_X \equiv \sigma\delta F_X$. These allow us to find average production values for domestic firms (domestic sellers and exporters) in terms of these fixed costs. Moreover, to solve for the entry thresholds we use the free entry condition, namely the equalization of the expected value of developing a variety and the investment cost in making a blueprint, ex-ante:

$$f_I = \int_0^{a_D}\left(\frac{a^{1-\sigma}}{\Delta}\mu R - f_D\right)dG[a] + \int_0^{a_X}\left(\phi\frac{a^{1-\sigma}}{\Delta}\mu R - f_X\right)dG[a] \tag{7}$$

We then solve for the threshold *a*'s to get:

$$a_D = \left[\frac{f_I}{f_D} \frac{1}{(\gamma - 1)(1 + \Omega)} \right]^{\frac{1}{k}} \qquad a_X = \left[\frac{f_I}{f_X} \frac{\Omega}{(\gamma - 1)(1 + \Omega)} \right]^{\frac{1}{k}} \tag{8}$$

While countries are identical in terms of production, exports and consumption, they have different emissions profiles since they have different emission technology β. Specifically, emissions at Home are:

$$E = n\zeta \ f_D \left[a_D{}^{\beta-1} + a_X{}^{\beta-1}\Omega \right]; \qquad \zeta \equiv \frac{k(\sigma - 1)}{(k - \sigma + \beta)\sigma} \tag{9}$$

Full derivation of this result is given in the Appendix. Foreign emissions take the same form, but with β^* in the place of β. Clearly every firm in the country with higher Beta can "translate" better its productive efficiency into cleaner production, and therefore has overall lower emissions. Notice that the emissions' module does not affect the deep mechanics of the model.

3.6. Policies and shocks

How does trade policy affect the industrial structure and emissions of the two countries in this model? We look at two distinct cases: symmetric trade liberalization and unilateral liberalization. We consider the symmetric changes first, since we can use the model as presented above. Looking as asymmetric changes requires us to introduce the possibility that countries have different size or different thresholds for market entry. This is done in sections 4.2.

We characterize as trade policy any tariff or regulation that affects the variable cost of trade, τ.[10] We start from the extreme case when the variable trade cost, τ, is prohibitively high, so that openness, Ω, is zero, and so is φ, the freeness of trade. By inspection of (8), the threshold productivity to access the export market a_X goes to zero, so no firms export. Logically, if variable trade costs are infinite, no matter how productive a firm is, there can be no exporting. As τ falls and trade gets liberalized, a_X increases so that the range of firms accessing the export market expands.[11] At the same time, we have a share-shifting and selection effect on the mass of firms, as described in the introduction. That is, the threshold

[10] We could otherwise look at the fixed entry cost in the foreign market, F_x, as this would still be captured by the catch-all measure of openness, Ω.

[11] If instead we want to look at fixed costs of exporting, the trade liberalization could derive from a change in the ratio of fixed costs of exporting, F_x, to fixed costs of domestic production, F_D. The higher the F_x/F_D ratio, the harder it is to access the foreign market relative to the domestic one, and therefore the lower the openness.

productivity to sell in the domestic market, a_D, falls due to the extra competition from new foreign firms. This means that the least efficient Home firms in the market – those that have profits barely sufficient to pay the fixed cost of producing – are forced out, and their market shares are reallocated to top firms, that now also serve foreign markets. These two interesting mechanisms, the selection effect on firms at the bottom of the distribution and the expansion of the top of the distribution in the export market, cannot be observed when firms are homogeneous. They are instead clear in this model, because of the change in the efficiency thresholds caused by trade. Fig. 2 illustrates the effect of different trade openness levels on a_D and a_X. The change in threshold values is where most of the action takes place also in terms of determining emissions per country, therefore it is very important to identify their change after trade liberalization. The effect of a tariff or other measures to increase variable trade costs would simply operate in the opposite direction.

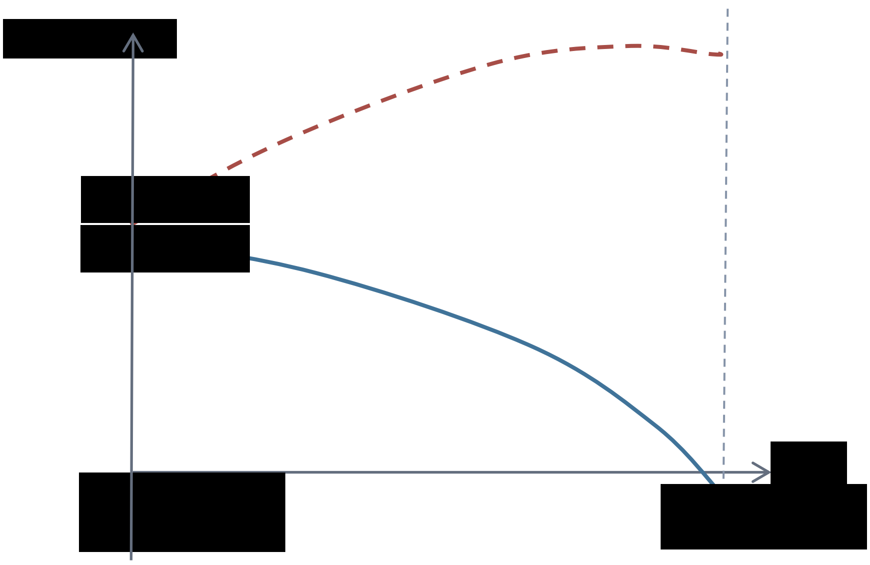

Fig.2 *– Effect of tariffs on productivity thresholds*

Which threshold changes more, in absolute terms? Are more productive firms exporting or more unproductive ones exiting? For the fall in the domestic threshold to be greater than the rise in the one of exporters, we need:

$$\frac{\partial(a_D)}{\partial\Omega} < \frac{\partial(a_X)}{\partial\Omega} \quad iff \quad \frac{b_D}{b_X} < \Omega^{1-k} \quad \Rightarrow \quad \frac{f_x}{f_d} < \Omega^{1-k} \text{ [12]} \tag{10}$$

[12] Or more precisely $(f_x / f_d)^{\psi} < (1+\tau)^{k(1-k)}$ where $\psi \equiv (2-2\sigma-k^2+k\sigma)/(k+1-\sigma)(1-k)$ (unambiguously positive if k >1).

Intuitively, an increase in trade openness has a negative effect on domestic firms, but allows more of the most efficient firms to export. Clearly, with lower trade costs, some firms that were previously producing for the domestic market start exporting, while the mass of domestic sellers reduces because some of the least efficient firms at the end of the distribution are wiped out by foreign competitors, as a_D falls. If fixed costs of entry in the export market is not too far from that of entering the domestic market, the effect on exporters is stronger than the destruction of less productive firms.

This is very important for emissions because we get two effects due to the trade liberalization: on the one hand, the least productive firms exiting the market – the selection effect - unambiguously reduce emissions, since the average technology of active firms improves; on the other, however, having more exporters means increasing the scale of production and hence more emissions, even if these are from the most efficient and cleaner firms.

3.7. Total Emissions

To see formally what happens to total emissions, we observe first what happens in terms of average output production:

$$\bar{x} = \frac{k(\sigma - 1)}{(k-\sigma)\sigma \ f_D}\left[\frac{1}{a_D} + \frac{\Omega}{a_X}\right] \tag{11}$$

As trade gets freer and Ω increases, the first term in squared brackets gets larger, while the second is more ambiguous, since both numerator and denominator increase (both a_x and, of course, openness, Ω). Even if the two thresholds were to move exactly by the same amount, overall average output would rise with trade openness. This is similar to what happens in terms of emissions, but mediated by the emission technology factor, β. Looking at emissions in (9), two transformations take place: one in the thresholds, as outlined above, and another in *n*, since also the number of firms is changed by trade. We can rewrite equation (9), plugging the results found above for *n* and the thresholds, to see more easily where Ω, the parameter for trade openness, plays a role.

$$E = n\zeta \ f_D\left(a_D{}^{\beta-1} + a_X{}^{\beta-1}\Omega\right) = \frac{\mu R}{\gamma(1+\Omega)}\zeta\left(\frac{f_I}{(\gamma-1)(1+\Omega)}\right)^{\frac{\beta-1}{k}}\left[\left(\frac{1}{f_D}\right)^{\frac{\beta-1}{k}} + \left(\frac{1}{f_X}\right)^{\frac{\beta-1}{k}}\Omega^{\frac{\beta-1}{k}+1}\right] \tag{12}$$

The derivative with respect to Ω is a complex mix of its effects. The effect on the number of producing firms is unambiguous: *n* falls as openness rises, due to the selection effect on the worst firms - as it can be seen in Fig. 3 below or by inspection of equation (A3) in the Appendix. This is inevitable since the average firm pays a higher fixed cost (more firms pay both F_D and F_X), and hence the average firm needs higher sales to cover the fixed cost. As the aggregate size of the world market does not change, higher average sales require fewer firms. This reduces emissions directly.

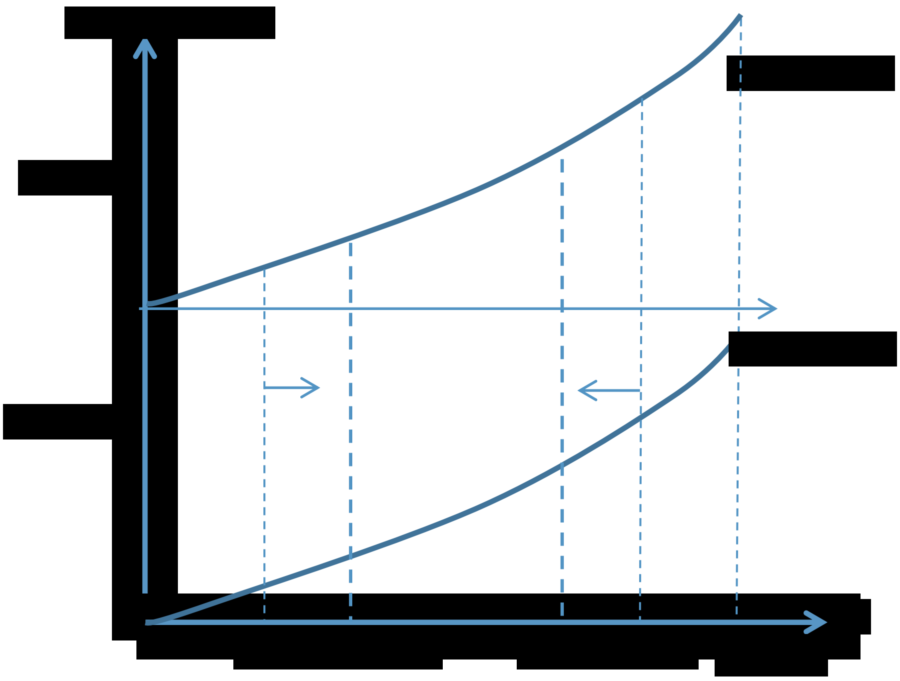

Fig.3 *– Effect of trade liberalization: firms' distribution "shrinks" from above and fewer firms (n) produce*

The first term in brackets of (12) is also always negatively affected by a rise in trade openness, as long as β > 1. The overall equation can rise or fall depending on whether the decrease in a_D dominates the increase in $a_X\Omega$ (second term in brackets). This happens asymmetrically in the two countries, given the different β. Intuitively, the environmental improvement can occur as some of the worst firms are wiped out and replaced by foreign importers. However as more firms now have access to trade, the outcome is not unambiguous. The point is that total output rises even as per unit emissions fall. Therefore the fall in per unit emissions must be large enough to compensate the expansion in size. Formally:

$$\frac{\partial E}{\partial \Omega} > 0 \quad iff \quad \underbrace{\frac{\partial n}{\partial \Omega} \zeta\, f_D \left[a_D{}^{\beta-1} + a_X{}^{\beta-1} \Omega \right]}_{>0} + \underbrace{n\zeta\, f_D \left[\frac{\partial \left(a_D{}^{\beta-1} \right)}{\partial \Omega} \right]}_{>0} > \underbrace{n\zeta\, f_D \left[\frac{\partial \left(a_X{}^{\beta-1} \Omega \right)}{\partial \Omega} \right]}_{<0} \tag{13}$$

Furthermore, total emissions are made of the sum of emissions in the two countries, hence it is the net effect on the sum of emissions that counts from a global perspective. Therefore it matters not only how much a country compensates higher production for trade with firms' selection, but also how the two countries relate and how production is shifted between the two nations. In order to illustrate more clearly the various possible scenarios, we set up our model with some reasonable calibration parameters (see Appendix), similar to those presented in Breinlich and Cuñat (2010) and Ghironi and Melitz (2005).

In the simplest case, we see that symmetric trade liberalization can reduce total emission, if emission technologies are sufficiently clean, as shown in Fig. 4. Of course the effect is not symmetric since the β differs between the two countries, and the dirtiest country (Home) starts with higher pollution in autarky, at φ=0. Note however the importance of "sufficiently clean" technologies: if β > σ, the increase in emissions due to expanding markets and substitution of goods are fully compensated by the efficiency-enhancing selection effect, that makes the country cleaner even with larger production. This is depicted in Fig. 4 as the blue solid line. In the opposite case, however, if β < σ, productivity improves emissions at the level of each unit of output produced, but not enough to compensate for the extra production of the best firm. Firms with small *a*, in fact, being more efficient, can sell more output with trade, depending on the elasticity of substitution between goods. The size effect might dominate and trade liberalization is not unambiguously good at all levels of openness (red dashed line).

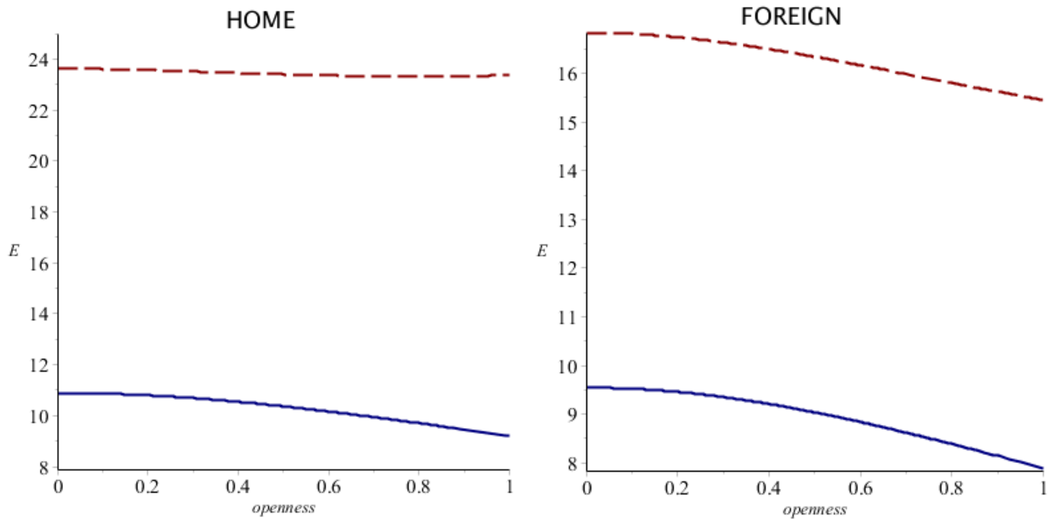

Fig. 4 *– Home (left panel) and Foreign emission (right) as trade openness - φ -rises. Home emits more than Foreign – due to lower β. The blue solid line represents β > σ, the red one β < σ.*

It clearly follows that global emissions, i.e. the sum of the two countries' emissions, fall unambiguously in the first case, when the emission technology is sufficiently clean, but not necessarily if one or both trading partners do not have emission technologies sufficiently clean to compensate for the higher output (Fig. 5 illustrates the effect on total emissions).

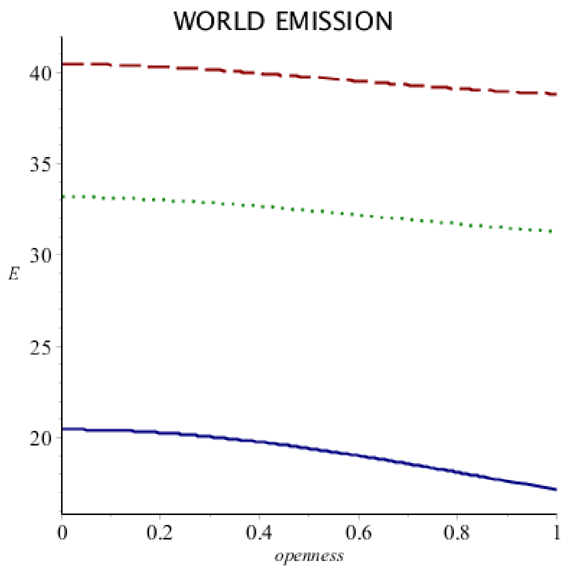

Fig. 5 *– Total emissions as trade openness rises. The blue solid line represents the case of both countries with β > σ, the red dashed one both with β < σ, and the green dotted one when Home has β < σ and Foreign β > σ.*

This can give rise to some particular situations whereas one option to reduce emissions would be to adopt some protective trade measures. Alternatively, if the countries do not want to impose trade barriers, for instance due to WTO regulations, the most advanced one could transfer some clean technology to the less clean one, to ensure that its emission profile goes to the situation depicted in the blue solid line.

This simple symmetric setting allowed us to build intuition for more complex cases, as it highlights a key prediction of this emission-augmented Melitz model. Namely, in so far as trade liberalization improves efficiency (via selection and expansion of the most efficient firms) and efficiency is negatively linked to emissions, we can get an improvement in total emissions – so long as the negative emissions-efficiency link is sufficiently strong. As shown above, the emission technology parameter that translates firms' productivity into pollution, β, is key to this mechanism. However this is not the only element that can affect the change in emission: importantly, country size and technological development may matter, as well. In the next sections, we want to consider other asymmetries as central issues, since global green-trade policy linkages arise mostly among highly asymmetric countries – think of China and the EU.

We therefore turn now to explore the extent to which the baseline result holds when nations differ in size (as captured by *R*) and technological capacity (as captured by parameters of the Pareto distribution). This allows us to state more generally what happens when one country puts up a tariff, a regulation, a carbon tax or some other protection, and for this we need a more flexible model design. This is the task of the next two sections.

4. ASYMMETRIC COUNTRIES

Counties do not differ only because of the emission technologies available to them. This section considers two important real-world scenarios: countries of different size and different productivity distribution. First of all, we model market size differences, as measured by domestic demand and expenditure, R. In this case, the price indices and the number of active firms differ between the two countries in equilibrium. The price indexes are indirectly defined by:

$$\Delta = \gamma \, a_D^{1-\sigma} \, (n + n^*\Omega), \; \Delta^* = \gamma \, a_D^{1-\sigma} \, (n^* + n\Omega) \tag{14}$$

where $\Delta \equiv [P(1-1/\sigma)]^{1-\sigma}$ and Δ^* is defined in an analogous manner. Note that *n* and *n** are not equal.

Even if the countries have the same fixed costs, operating profits differ across firm-type and across markets. There are then four distinct cut-off conditions (two for Home and two for Foreign). These are:

$$\frac{a_D^{1-\sigma}}{\Delta}\mu R = f_D \qquad \phi\frac{a_X^{1-\sigma}}{\Delta^*}\mu R^* = f_X \qquad \frac{a_D^{1-\sigma}}{\Delta^*}\mu R^* = f_D \qquad \phi\frac{a_X^{1-\sigma}}{\Delta}\mu R = f_X \tag{15}$$

Note again that *R* and *R** are not equal. The cut-offs depend on the number of active firms, so *n* and *n** must be determined simultaneously (see Appendix):

$$n = \frac{\mu}{\gamma \; f_D}\frac{(R - R^*\Omega)}{(1-\Omega^2)} \qquad n^* = \frac{\mu}{\gamma \; f_D}\frac{(R^* - R\Omega)}{(1-\Omega^2)} \tag{16}$$

As it turns out, even with different country size, the cut-offs for a_D and a_X are the same as in the case of symmetric nations. The intuition is simply that n and n* adjust up to the point where the marginal firm is indifferent between the two markets, so the ‘effective’ market size, R/Δ, from the firm’s perspective is equalised between the two nations. As R/Δ and R*/Δ* become equal, the thresholds are identical to the symmetric countries case:

$$(a_D)^k = \frac{f_I}{f_D}\frac{1}{(\gamma-1)(1+\Omega)} \qquad (a_X)^k = \frac{f_I}{f_X}\frac{\Omega}{(\gamma-1)(1+\Omega)} \tag{17}$$

Despite this similarity to the symmetric countries case, total emissions depend crucially also on country size and are thus asymmetric in the case at hand. We can see that what matters now is the interplay between emission technology, β, and country size.

$$E = n\zeta \; f_D \left[a_D^{\beta-1} + a_X^{\beta-1}\Omega\right] \qquad E^* = n^*\zeta \; f_D \left[a_D^{\beta^*-1} + a_X^{\beta^*-1}\Omega\right] \tag{18}$$

In this set up, we can consider a wider range of scenarios: there can be a situation whereby a country has worse emission technology, but if it is significantly smaller than its trading partner it emits less. Or, vice versa, we can consider the case of a country like China, where the problem of emissions is compounded by its huge market size.

4.1. Trade policy and asymmetric size

Changing the variable cost of trade, τ, or fixed costs F_X, produces economic effects as those studied in Baldwin and Forslid (2010). For variable costs liberalization (lower τ) with nations of different size, we get a *Home Market Effect* (HME), so the share of a nation's production rises more than proportionally in the big country, while falling in the other, via changes in n and n^*. Given this effect, the interaction between relative size and relative emission intensity (as measured by β) is critical for the total effect on emissions. If the larger country is also the dirtiest, trade liberalization allocates production more than proportionally to the larger, dirtier nation. This effect alone worsens total pollution, however the selection effect works in the opposite direction, offsetting part of the extra pollution by making both nations more carbon-efficient. In other words, country size and emission technology act in combination: the larger country gets more and more production as trade is liberalized, and this can be good or bad for the environment depending on its emission technology. The case of a country like China could be therefore a problematic one, because due to its sheer size it would attract large shares of production as it gets more integrated in the world economy, but if this is not coupled with clean emission technologies it could produce large increases in overall emissions.

Fig. 6 illustrates the two opposite cases: when Foreign is larger than Home, and hence the larger country is also the cleanest one (left panel) and when Home is the largest, so the big country is the dirtiest (right panel).[13] The differences are striking. In the first case, $N<N^*$, the allocation of production caused by the Home Market Effect is environmentally friendly and trade liberalization always reduces emissions. Even if emission technologies are not very good in both countries (red dashed line), as the larger, cleaner country gets a larger share of world production, world emissions fall. Instead, if the dirty country dominates in terms of market size, trade openness reallocates productive activities to dirty firms, and therefore globally emissions can increase if emission technologies are not sufficiently clean. If the dirtiest is also the largest country ($N>N^*$), trade is beneficial only if both have $\beta > \sigma$ (blue solid line). If the dirty country (green dotted) or both (red dashed) have $\beta < \sigma$, trade liberalization raises emissions.

[13] We always assume that Home's emission technology is on average worse, so $\beta < \beta^*$.

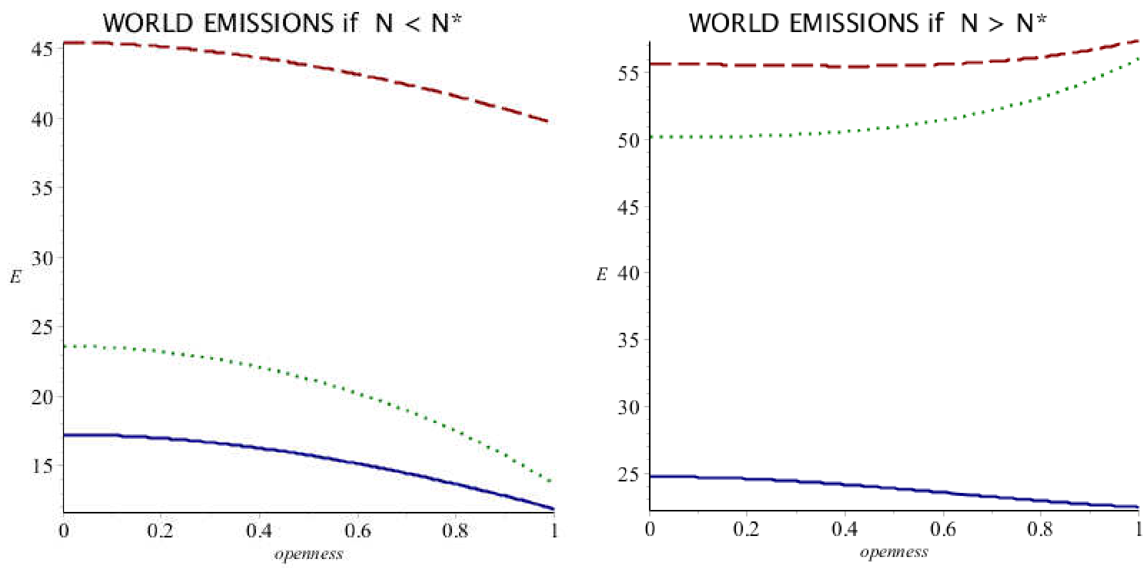

Fig. 6 *– Total emissions and size. Red dashed line: both countries with "bad" emission technologies, β < σ; blue solid line: both countries have β > σ; green dotted line: Home has β < σ, while Foreign has β* > σ *.*

This scenario gives a useful indication about what would happen in case of a demographic boom or a large increase in purchasing power. By boosting the size of a developing country that uses polluting technologies, the exogenous growth factors tend to worsen the environment. More to the point, greater relative size asymmetries make the Home Market Effect stronger, so even at a given level of trade liberalization the demographic increase is likely to worsen emissions, if emission technologies are not good enough to compensate the size effect. Again, one way to counter this tendency is to lower the big nation's β via green technology transfers. However if the two nations are too different in size or in their beta technologies, it might require a very large effort to make trade openness unambiguously beneficial for the environment. [14]

In other words, size can greatly magnify the problem of emissions linked to trade openness, since it determines the allocation of production among countries, and it could bring most economic activities to the dirtiest country, if this is larger. The selection effect on the tails of the firms' distributions still operates, but it might require even more advanced clean technologies to ensure that total emissions are not worsened by trade.

[14] If we use for the parameterization of the emission function depicted in Fig. 6 more extreme values, raising the difference in countries' size or betas, we get in the right panel that t high levels of openness can cause a rise in emissions even when the emission technology parameter beta fully compensates sigma in both nations.

Next, we consider the case where the two countries are asymmetric in their *production* technologies (their firms' distributions). This is useful to analyse the case of polluting nations whose productivity pattern is far yet approaching that of advanced economies.

4.2. Different entry thresholds

If the countries differ in the dirtiness of their technologies and also in terms of the productivity distribution of their firms, the thresholds for market entry become asymmetric between the two nations. This case can also arise if trade barriers are not symmetric, and if only one country decides to implement a tariff. We therefore need a more flexible set-up that can account for this possibility. Suppose the productivity distribution of the Foreign country first order stochastically dominates[15] the one for Home, so Foreign is always more productive than Home. With the Pareto distribution, we can capture such outcome by imposing different shape parameters *k* or different scale parameter a_0.

Other things equal, expected profits in the country with a better productivity distribution are higher, since entrants have a better chance to obtain a productivity draw below the domestic entrance threshold. This implies that the optimal entry cut-off is lower in the most efficient country, because given the better chances of a winner, there is more competition (proof: see Appendix). If we assume that the Foreign country has a better distribution of productivity, we get that the thresholds are:

$$a_D > a_D^*$$

The intuition here is simple. The free entry tends to equalise firm-level market size as discussed above, but the skewedness of the distribution towards low-cost firms in the Foreign market, means that the marginal D-type firm in Foreign must be more competitive than the marginal D-type in Home.

Correspondingly, the skewed distribution of low cost firms means that Foreign firms find it easier to access the Home market than for Home exporters to access Foreign's market. Thus:

$$a_X^* > a_x$$

Overall, given the regularity condition that exporting thresholds are lower than domestic ones, we get

[15] Demidova (2008) notes that if we do not use the Pareto distribution, it might be necessary to use a more restrictive concept of dominance, such as Hazard Rate Stochastic Dominance (which implies first order SD, but not viceversa).

$$a_D > a_D^* > a_X^* > a_X \quad (19)$$

Thresholds are different, however they are linked between countries. To be precise:

$$a_X = A\, a_D^* \qquad a_X^* = A\, a_D \qquad A \equiv \left(\frac{\phi f_D}{f_X}\right)^{\frac{1}{\sigma-1}} > 1 \quad (20)$$

Using this information, we can solve for the equilibrium. Derivation of the price index and the number of active firms is given in the Appendix, following Demidova (2008).

4.3. Unilateral Trade Barriers

With this more flexible set up, we can turn now to the effect on emissions of *asymmetric* trade policies. For example, in an effort to improve the global environment, Foreign might consider unilateral trade barriers against Home's exports (remember that Home is the dirty developing nation). We model this as an ad valorem tariff that enters only Home's trade costs, so that its exporters will face less openness, $\phi \equiv \tau^{1-\sigma} < \phi^* \equiv \tau^{*1-\sigma}$ (so for every unit sold abroad, they must pay a higher cost). This extra cost is reflected in a decrease in Home's catch-all openness parameter, Ω, making it different from Ω*. This changes the number of active firms and the market entry thresholds.[16]

Before turning to the calculations, intuition is served by examining the effects informally. Raising Foreign protection unilaterally makes it hard for Home firms to export, so obviously the Home export thresholds falls (firms need lower marginal costs to export). On the whole, the firms previously exporting go back to compete on the domestic market, therefore pushing out some Home domestic sellers, thus lowering the equilibrium *n*. The shift from export to domestic market competition in Home has also consequences abroad. First, it reduces the competition from imports in Foreign's domestic market, therefore more firms can be accommodated (*n** raises). This can relax the entry constraint at the bottom end of the Foreign efficiency schedule. Also, it can make it marginally harder for Foreign firms to export, since the Home market has become more competitive. In this sense, import protection in Foreign tends to harm Foreign exports, indirectly. However, all these effects on

[16] Baldwin and Forslid (2006) perform a similar exercise but assume that the freeness of trade increases symmetrically for both countries, thanks to a trade liberalization. In that case omega rises, but remains the identical for both nations, and thresholds move in parallel in the Home and Foreign country ($a_D \downarrow, a_X \uparrow$).

the number of firms and thresholds are hard to disentangle analytically. The impact on emissions is ambiguous and depends on the parameterization of the problem. World emissions are as our usual metric:

$$E^{world} = \zeta \ f_D \left[n \ \left(a_D{}^{\beta-1} + a_X{}^{\beta-1}\Omega \right) + n* \ \left(a*_D{}^{\beta*-1} + a_X{}^{\beta*-1}\Omega* \right) \right] \tag{21}$$

Again, we resort again to a simple parameterization of the problem to observe the various possible scenarios. First of all, we can now observe what happens to total emissions with different, asymmetric trade policies. These policies affect the thresholds in the two countries. In Fig. 7, we see what happens to Home emissions if any of the two countries liberalizes trade. If Home has the technological capacity to compensate for the extra output deriving from trade, so *β > σ,* any trade liberalization policy, either implemented from Home or from its trading partner, unambiguously operates the Melitz-style selection effect and emissions at Home fall (left panel). However this is not the case when the emission technology is not sufficiently clean, and *β < σ* (right panel): some liberalization can be beneficial for the environment – e.g. when Home market is completely closed, and Foreign completely open, Home's opening up to competition can reduce emissions – however there are reasons for the Foreign trade partner to impose trade barriers , as indicated by the red arrows, to reduce Home emissions, since the lowest point for emissions is when Foreign is only partially open.

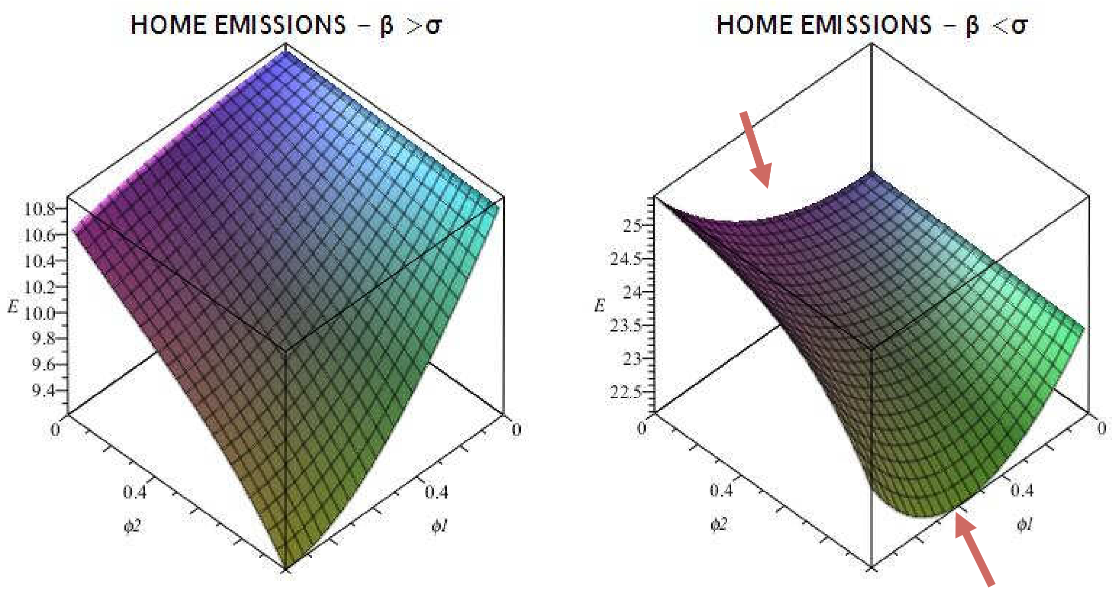

***Fig. 7** – If Home compensates the increase in output from trade liberalization and β>σ (left), total emissions unambiguously fall with trade liberalization. This is not the case when β<σ (right).*

The story depicted in Fig. 7 is similar for the Foreign country, just with better β parameters and therefore lower emission levels to begin with. For global emissions, the sum of Home and Foreign is shown in Fig. A1 in the Appendix. It follows clearly from the case illustrated above that if both countries have sufficiently clean emissions parameters, $\beta > \sigma$, any policy for freer trade from any of the two countries makes global emissions fall unambiguously. If, however, this is not the case, and Home's technology is too dirty, so that $\beta < \sigma$, there is scope for some unilateral trade policies that reduce openness to reduce global emissions. This is similar to Kreickemeier and Richter (2014), who find that in the case of a unilateral trade liberalization the optimal tariff might be positive. In this case, however, if only Home has insufficiently clean technology to compensate the extra output, trade protection is beneficial only from the side of the Foreign, the cleanest trade partner. Trade liberalization from the side of Home, instead, always reduces world emissions because the cleanest firms are selected. Only if both countries have insufficiently clean emission technologies, there is scope for trade protection from both sides.

What matters most is the interplay between trade policies and technological capacities: if the technology is good enough, both countries can benefit from trade from an environmental standpoint; the problems arise in the case of technological backwardness. Again, it could be argued that R&D or technology transfers could be better measures that trade protectionism to achieve lower global emissions.

Next, we can look at what happens when the countries have different productivity distributions. Assume Foreign is the most productive nation; as usual, trade liberalization creates more competition, hence the domestic entry threshold falls and, as a consequence, as shown in (20), also in the export cut-off for Home. This is due to the selection effect from enhanced competition faced by firms. But as Demidova (2008) showed, the effect on the other two thresholds is not so straightforward. In terms of emissions, this scenario is depicted in Fig. 8: the "backward" country, benefits from trade openness unambiguously in terms of local emission reductions, because its dirty firms are substituted by Foreign imports – and now Foreign is even cleaner, not only because of its emission technology β, but because its whole distribution is more skewed towards cleaner firms. Overall, what is interesting is that in this case the role of β with respect to sigma σ is significantly reduced: for the Home country it no longer matters, except for the absolute level of emissions (scale of the vertical axis in Fig. 8), but the relationship with trade openness is always the same.

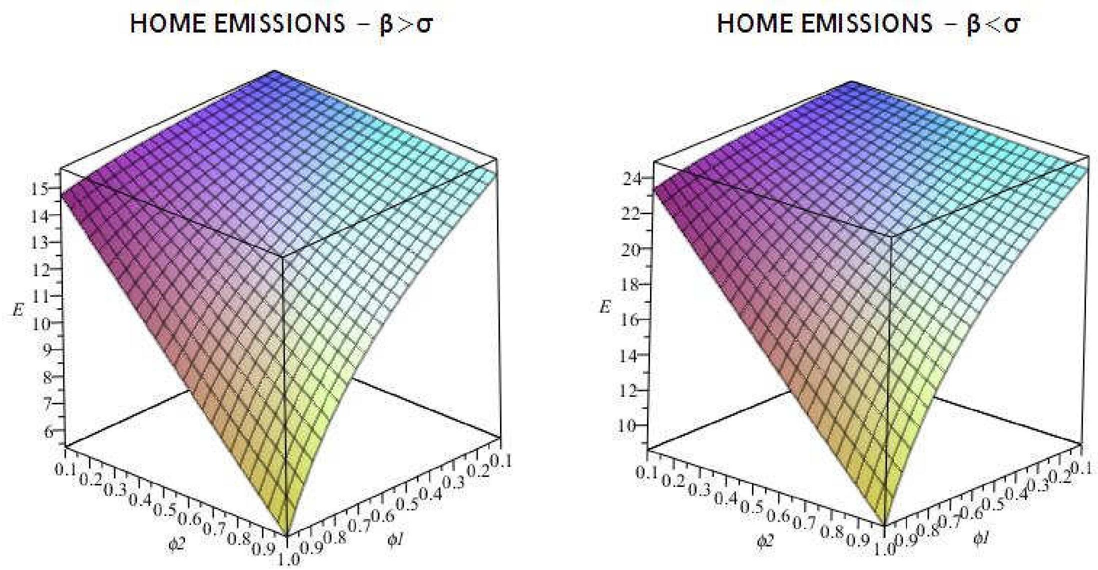

***Fig. 8** – Home emissions fall with openness, independently of the relationship between β and σ.*

For the most advanced country, the effect on emissions is ambiguous and depends also upon β (Fig. 9). In general, the most productive and cleanest country risks to lose more from opening up to trade with a dirty, inefficient partner in terms of own emissions.

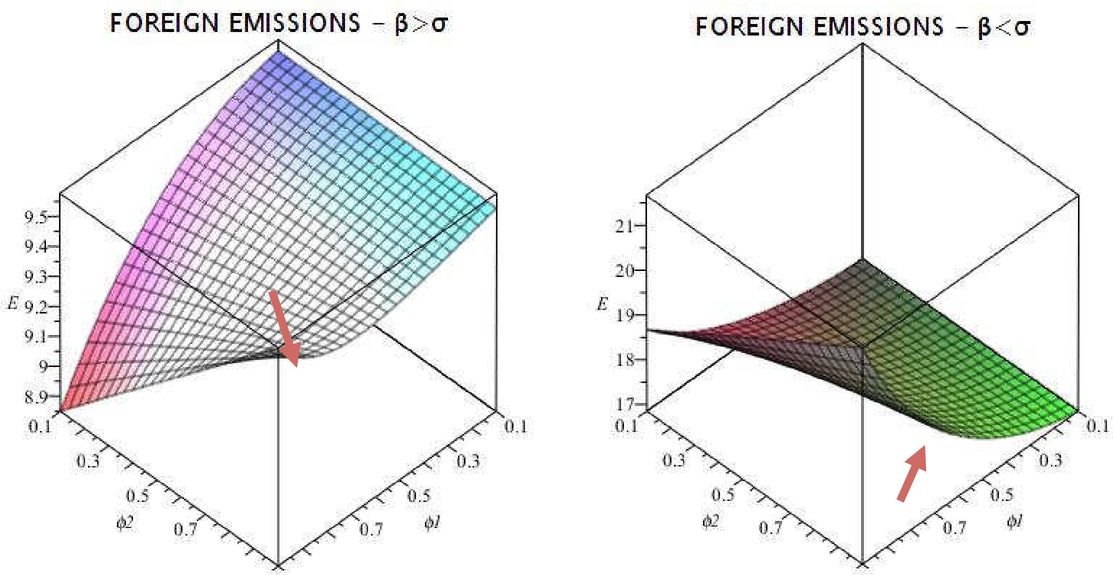

***Fig. 9** – Foreign emissions don not always fall with openness, depending on β.*

However, the effect on world emissions can still be positive, if the fall in emissions in the dirty country fully compensates the rise in emissions in the cleanest, more productive trade partner. Depending on how technologically distant are the two nations, we can get that trade is always beneficial for overall emissions, or that there are some "leakages" caused by trade liberalization (Fig. A2 in the Appendix).

4.4. Technological convergence

We can now examine the effects of an improvement in the productive technology of the least advanced nation. If Home, the backward country, improves its technology and lowers labour input requirements, *a*, its market becomes more competitive and on average emission per unit of output fall. This is bad news for the least efficient Home producers and Foreign exporters, as the thresholds to enter that market become tougher, as a_X^* and a_D fall. Conversely, the other thresholds rise, as the Foreign market becomes relatively less competitive, so more firms will be able to operate there. This effect on thresholds is similar to what is shown in Demidova (2008:1454). In terms of environmental impacts, there are two effects of these shifts: one directly on total emissions, and another on the relationship between trade openness and emissions. In terms of the absolute value of emissions, technology improvements are accompanied by lower emissions overall. This result is quite intuitive, given the linkage between productivity and emissions discussed in (4).

Secondly, the relationship between emissions and trade openness changes depending on how different the two countries' productivity distributions are. When the countries differ substantially, trade openness benefits more the backward country, even when $\beta < \sigma$. If the two countries are instead identical in their productivity, it is more likely that there will be some "leakages", especially when the emission technology is not very advanced. Again, the possibility of technology transfers and investments in the emission technologies can significantly improve global emissions in both scenarios.

In the case of a technological catch-up from Home, the less developed nation, there would be the first order effect of a cleaner, more productive distribution of firms, and a second order effect that coming closer to the distribution of the advanced nation will cause more potential leakages of trade openness. Therefore trade protectionism from the side of Foreign could be justified in the short run to prevent leakages. However, even if here we do not model explicitly the reasons for the technological improvement, it is likely that imposing trade barriers would not help the developing country to catch up with the rest of the world. The use of technology transfers would be as effective, and would not cause deadweight losses and distortions as much as imposing a tariff. Moreover, if the technological transition takes place at the same time as a demographic one, as it is the case in many developing nations, what matters is whether the demographic increase will causes more pollution through the Home Market Effect, or if this will be compensated by the better distribution of firms' productivity, which acts as a selection force on the dirtiest and oldest producers.

5. DISCUSSION

The above analysis is only a first exploration of the whole spectrum of possible policies and shocks that countries can face in their economic and environmental interactions. Allowing for firm-level heterogeneity is an important direction in which to expand the existing theory. Some interesting conclusions can be drawn from the previous analysis, which are of particular relevance for policy decisions; and several further avenues for research can develop from here, specifically looking at other combinations of policies.

The main points of our theory concern the mechanisms through which trade policy affects global emission. A key point is that trade liberalization is good for environmental efficiency due to its selection effect, in particular the way it eliminates the highest cost, most polluting firms. This mechanism, however, may be offset by the standard output effect (increases in GDP and thus emissions, other things equal). The overall effect depends on how strongly the firm-level emissions technology compensates for the extra output. A second key channel turns on the Home Market Effect, whereby freer trade tends to shift industrial production to the larger nations – even when trade barriers are symmetric. If the large nation is also the one with the worst emissions problem, freer trade can easily worsen the global environment. The case of China comes to mind when pondering this example. Our theory, however, reveals that a properly proportioned package of green-technology transfers and freer trade can unambiguously reduce global emissions. Finally, asymmetric production technologies provide a further channel, such that trade liberalization can be good for the more backward country, but might damage the more advanced one in terms of its emission profile. This case would call not only for transfers of green technology, but also for a catch-up in overall productivity by the developing nation.

Beyond these points, several more subtle issues can be addressed. Our paper does not focus on transitions (relying on equilibria analysis), but we conjecture that the intuition flowing from the model helps thinking through transition dynamics, as well. In a framework where the speed of adjustment depends upon the death rate of existing firms, we can image a situation where a developing nation has a stock of dirty firms, but also a flow of new, clean firms entering. This overall works as a technology improvement on the distribution of firms, and benefits the environment. In such a world, trade barriers against the developing nation's exports could slow the transition and thus worsen emissions – even if they were intended to achieve the opposite outcome. If less efficient, dirtier firms exited sooner endogenously (so δ, the death rate, was not just a random shock, but a function of efficiency, a), the replacement of old polluting firms due to a technology improvement or trade liberalization would be faster. This might suggest implementing, as environmental policy measures, some incentives for the replacement of old plants.

Our paper also did not directly address widely discussed issues of 'unfair' competition. For example, countries with dirty emission technologies, such as China, might enjoy a competitive advantage given by the fact that they can produce dirtier without bearing the cost of it. We could model this by representing the productivity distribution of the dirty nation as being "artificially" closer to that of the clean nation, since the unit labour costs a in the clean nation include environmental costs that firms in the dirty nation do not bear. This 'dirty comparative advantage' can be modelled, as shown in Section 4.4, as technological convergence, or a productivity improvement that the backward country enjoys, even if it is actually a cost-cutting strategy. However this would not lead to a reduction in the total level of emissions, since now the improved marginal costs would not match with better emission technologies.

A final possible extension would be to re-consider the pollution heaven effect arising from regulation and firms' relocation. Similarly to Baldwin and Okubo (2009), who looked at relocation with different taxation regimes in the presence of heterogeneities, our framework could allow for the tails of the productivity distributions to relocate to the country which allows for more pollution.

The basic thrust of this whole analysis is that ignoring firm-level heterogeneity – as is done in most of the literature – misses several important links between trade and the environment. Hence it is important that policymakers are aware of these heterogeneous effects.

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APPENDIX

Section 3 - Derivations

3.4. Solving for the open-economy equilibrium in baseline model, we starts from the price index, which is expressed as a weighted average of marginal costs:

$$\Delta \equiv [(1-1/\sigma)P]^{\frac{1-\sigma}{\mu}} = n\int_0^{a_D} a^{1-\sigma} dG[a \mid a_D] + n^* \tau^{1-\sigma} \int_0^{a_X^*} a^{1-\sigma} dG[a \mid a_D^*] \tag{A1}$$

The first term is the marginal costs' index for domestic producers, up to the a_D threshold, while the second is for foreign firms that export to the Home country. Since the two nations are symmetric, thresholds are equivalent, and *n=n**, so the price indexes are symmetric. Using the Pareto distribution, and assuming the regularity condition k > σ-1, the integrals solve to give:

$$\Delta = \gamma \ a_D^{\ 1-\sigma} \ n \ (1+\Omega) \tag{A2}$$

where $\gamma \equiv \dfrac{k}{1-\sigma+k} \geq 1$, $\quad \Omega \equiv \phi \ (a_X / a_D)^{1-\sigma+k} = \phi^{\frac{k}{(\sigma-1)}} (F_X / F_D)^{1-\frac{k}{(\sigma-1)}}$ and $\quad \phi \equiv \tau^{1-\sigma}$ represents the freeness of trade, which ranges from zero with infinite trade costs/barriers to unit with no such costs. The parameter ϕ is the main trade policy instrument that our countries use as it encompasses, via τ, ad valorem tariffs and related trade measures. Ω encapsulates both variable trade barriers via τ and fixed barriers as captured by F_X/F_D, namely the extent to which entry is more difficult for foreign firms than it is for domestic firms. Plugging the price index in the cut-off conditions (6), we solve for *n*: [17]

$$n = \frac{\mu R}{\gamma \ (1+\Omega) f_D} \tag{A3}$$

[17] We could also look at labour allocation and mass of firms that produce for the domestic market and for exports: total labour force L is allocated between covering the fixed costs and to variable production:

$$L = M^e F_I + M^D F_D + M^X F_X + M_D \int_0^{a_D} a_i c_i dG[a|a_D] + M_X \int_0^{a_X} a_i c_i dG[a|a_X]$$

Using the facts that out of all firms that try their luck drawing from the Pareto distribution (the mass of entrants, M^e), a firm must draw a number of times before it gets an *a* lower than the production cutoff, a_D, and similarly the probability of getting an exporter productivity conditional on having drawn below a_X, we can solve for the mass of domestic producers dedicated to the home and foreign market:

$$M_D = \frac{(\sigma-1)L}{f_I k} a_D^{\ \kappa} \qquad M_X = \frac{(\sigma-1)L}{f_I k} a_X^{\ \kappa}$$

To close the model, we use the free entry condition (7) and find the two thresholds. For more detail on the calculation of thresholds, we refer the reader to pp. 25 of Baldwin and Forslid (2010) working paper (Guide to calculation).

Solving for total emissions, we sum up emissions in (4) for all firms in a nation:

$$E = n\int_0^{a_D} \left(a^{\beta} c(a)\right)\, dG[a \mid a_D] + n\int_0^{a_X} \left(a^{\beta} c^*(a)\right)\, dG[a \mid a_D] \tag{A4}$$

where *c(a)* and *c*(a)* are given by (3). Using the formulas above, we can express this as:

$$E = n\int_0^{a_D} \left(a^{\beta-\sigma} \frac{\mu R}{\Delta}\left(\frac{\sigma-1}{\sigma}\right)\right) dG[a \mid a_D] + n\int_0^{a_X} \left((1+\tau)^{-\sigma} a^{\beta-\sigma} \frac{\mu R}{\Delta}\left(\frac{\sigma-1}{\sigma}\right)\right) dG[a \mid a_D]$$

And using the Pareto distribution this solves to:

$$= n\frac{k(\sigma-1)}{(k-\sigma+\beta)\sigma}\frac{\mu R}{\Delta}\left[a_D{}^{\beta-\sigma} + a_X{}^{\beta-\sigma}\left(\frac{a_X}{a_D}\right)^k (1+\tau)^{-\sigma}\right]$$

Using the cutoff conditions (6), we can rearrange this as

$$= n\frac{k(\sigma-1)}{(k-\sigma+\beta)\sigma}\left[f_D a_D{}^{\beta-1} + f_X a_X{}^{\beta-1}\left(\frac{a_X}{a_D}\right)^k\right]$$

And finally, collecting f_D, using the ratio of cutoffs and rearranging the definition of Omega, we get the result in (2.12)

$$= n\zeta\ f_D\left[a_D{}^{\beta-1} + a_X{}^{\beta-1}\frac{f_X}{f_D}\left(\frac{a_X}{a_D}\right)^k\right] = n\zeta\ f_D\left[a_D{}^{\beta-1} + a_X{}^{\beta-1}\Omega\right]; \qquad \zeta \equiv \frac{k(\sigma-1)}{(k-\sigma+\beta)\sigma}$$

3.5 Formally, the change in thresholds with respect to trade openness is:

$$\frac{\partial(a_D)}{\partial\Omega} = -\frac{b_D{}^{1/k}}{k}\frac{1}{(1+\Omega)^{\frac{1}{k}+1}} < 0 \qquad \frac{\partial(a_X)}{\partial\Omega} = \frac{b_X{}^{1/k}}{k}\frac{1}{(1+\Omega)^{\frac{1}{k}+1}}\Omega^{\frac{1}{k}-1} > 0 \tag{A5}$$

where $b_D \equiv \dfrac{f_I}{f_D(\gamma-1)} \le b_X \equiv \dfrac{f_I}{f_X(\gamma-1)}$.

Section 4 - Derivations

4.1. Solving simultaneously for n and n*: again, see Guide to calculation in Baldwin and Forslid (2010), pp. 26. It is sufficient to solve simultaneously the two domestic cutoffs in (15) for n and n*.

4.2. Solving the equilibrium when the firms' distributions differ between countries: the most efficient country (lower shape parameter of Pareto distribution, *k*) has higher expected profits.

$$E(\pi)=(\gamma-1)\left[f_D+\left(\frac{a_X}{a_D}\right)^k f_X\right]=f_D(\gamma-1)(1+\Omega)=\left(\frac{\sigma-1}{k+1-\sigma}\right)\left[f_D+\left(\frac{a_X}{a_D}\right)^k f_X\right] \qquad \text{(A6)}$$

$$\text{where} \quad \gamma\equiv\frac{k}{1-\sigma+k}\geq 1$$

The first term in parentheses, $(\gamma-1)$, is clearly greater for the country with lower *k*. The second term, in squared brackets, is also greater the smaller the *k*, since the ratio of cut-offs is smaller than 1 (as $a_X<a_D$). Overall, expected profits decrease the higher the *k*.

In order to solve for the productivity cut-offs, we need first of all to establish a relationship between the thresholds of different countries:

$$a_x=Aa^*_D \quad a^*_x=Aa_D \quad A\equiv\left(\frac{\phi f_D}{f_X}\right)^{\frac{1}{\sigma-1}}>1 \qquad \text{(A7)}$$

To see why this is the case, use the ratio of domestic cut-offs in the two countries, that of export cut-offs, and then the ratio of a domestic and exporters' cut-off: even if price indexes and market size differ in the two countries, as long as the countries have same entry costs for the domestic and foreign market, the above relationships hold.

$$\text{X1}\equiv\frac{a_D{}^{1-\sigma}\mu R}{\rho P^{1-\sigma}}=f_D \qquad \text{X2}\equiv\frac{a^*{}_D{}^{1-\sigma}\mu R^*}{\rho P^{*1-\sigma}}=f_D \qquad \text{X3}\equiv\frac{\phi 1 a_X{}^{1-\sigma}\mu R^*}{\rho P^{*1-\sigma}}=f_X$$

$$\text{X4}\equiv\frac{\phi 2 a^*{}_X{}^{1-\sigma}\mu R}{\rho P^{1-\sigma}}=f_X$$

$$\frac{X1}{X2}=1\Rightarrow\frac{a_D}{a^*_D}=\frac{P}{P^*}\left(\frac{R^*}{R}\right)^{1/1-\sigma}\qquad\frac{X3}{X4}=1\Rightarrow\frac{a_X}{a^*_X}=\frac{P^*}{P}\left(\frac{R}{R^*}\right)^{1/1-\sigma}$$

$$\frac{X1}{X3}=\left(\frac{\phi 1 f_D}{f_X}\right)^{\frac{1}{1-\sigma}}\Rightarrow\frac{a_D}{a_X}=\frac{a^*_D}{a^*_X}=\frac{P}{AP^*}\left(\frac{R^*}{R}\right)^{1/1-\sigma}$$

$$\frac{a_D}{a^*_D}=\frac{Aa_D}{a_x}\Rightarrow a_x=Aa^*_D\qquad\frac{a^*_X}{a_X}=\frac{Aa_D}{a_x}\Rightarrow a^*_x=Aa_D \tag{A8}$$

Therefore we confirm the link between thresholds in different countries, $a_x=Aa^*_D$ and $a^*_x=Aa_D$.

- The price index can be rearranged, using the information from the cut-offs, as

$$\Delta=\gamma\left[na_D^{1-\sigma}+n^*\phi_H\left(\frac{a^*_X}{a^{*k}_D}\right)^{1-\sigma+k}\right]=\gamma\left[na_D^{1-\sigma}+n^*\phi_H\left(\frac{a^*_X}{a^*_D}\right)^k a^{*\,1-\sigma}_X\right]=\gamma\ a_D^{1-\sigma}\left[n+n^*\phi_H\left(\frac{f_X}{\phi f_D}\right)^{\frac{k}{1-\sigma}}A^{1-\sigma}\right]$$

$$\Delta=\gamma\ a_D^{1-\sigma}\left(n+n^*\Omega\right)\qquad\Delta^*=\gamma\ a^{*\,1-\sigma}_D\left(n^*+n\Omega^*\right) \tag{A9}$$

And we can solve for *n* and *n** from the cut-offs, which is the same as in the case of Section 4.1.

$$n=\frac{\mu(R\phi}{\gamma\ f_D}\frac{-R^*\phi^*\Omega^*)}{\phi^*(1-\Omega\Omega^*)}\qquad n^*=\frac{\mu(R^*\phi^*}{\gamma\ f_D}\frac{-R\phi\Omega)}{\phi(1-\Omega\Omega^*)} \tag{A10}$$

In order to solve for the single cut-offs, then we use the above result and two free entry conditions, one for Home and one for the foreign country.

Home: $$f_I=\int_0^{a_D}\left(\frac{a^{1-\sigma}}{\Delta}\mu R-f_D\right)dG[a]+\int_0^{a_X=Aa^*_D}\left(\phi^*\frac{a^{1-\sigma}}{\Delta^*}\mu R^*-f_X\right)dG[a]$$

(A11)

Foreign: $$f_I=\int_0^{a^*_D}\left(\frac{a^{1-\sigma}}{\Delta^*}\mu R^*-f_D\right)dG[a]+\int_0^{a^*_X=Aa_D}\left(\phi\frac{a^{1-\sigma}}{\Delta}\mu R-f_X\right)dG[a]$$

(A11b)

We can then express the results for Home domestic threshold as a function of the Foreign domestic threshold, and then see the point where the curves intersect (see also Demidova

2008). The results are quite complex, therefore it is not possible to see analytically the effect of a change in Omega on emissions. We resort to graphical illustrations to exemplify more clearly the effects of trade policies. Intuitively, if Foreign imposes trade barriers, these affect the Home thresholds directly through the cost of accessing the foreign market; however, even if the openness of Home remains constant, also the thresholds of the Foreign country are affected through their price index.

Calibration parameters

Here are the various parameters used to produce the graphs in the paper for total emission. Note that countries are always symmetric in their fixed costs $F_I=F_I^*$,$F_D=F_D^*$, $F_X=F_X^*$, and elasticity of substitution $\sigma=\sigma^*$.

	Baseline ($\beta \neq \beta^*$) (*Fig.4*)	$\beta < \sigma$ and $\beta^* < \sigma$ (*Fig.5*)	Different size (*Fig. 6*)		Different trade policies (*Fig. 7*)	Different production technology (*Fig. 8- 9-A2 left panel*)	Different technology (*Fig. A2, right panel*)
μ	0.5	0.5	0.5	0.5	0.5	0.5	0.5
σ	4	4	4	4	4	4	3
F_I	1	1	1	1	1	1	1
F_D	2	2	2	2	2	2	2
F_X	5	5	5	5	5	5	5
k	6	6	6	6	6	**9**	**9**
k*	6	6	6	6	6	**6**	**4**
R	100	100	**50**	**200**	100	100	100
R*	100	100	**200**	**50**	100	100	100
β	4.5 or 2	2	4.5 or 2	4.5 or 2	4.5 or 2	4.5 or 2	2
β^*	5 or 3	5	5 or 3	5 or 3	5 or 3	5 or 3	3

To compare with similar studies with heterogeneous firms, Ghironi and Melitz (2005) use μ=.824, σ=3.187, F_I=1, F_X =0.036 and k=3.4, while Breinlich and Cuñat (2010) σ=9, F_D =11, F_X =15 and k=16. We try not to diverge too much from these studies in our choice of parameters.

World Emissions - Figures

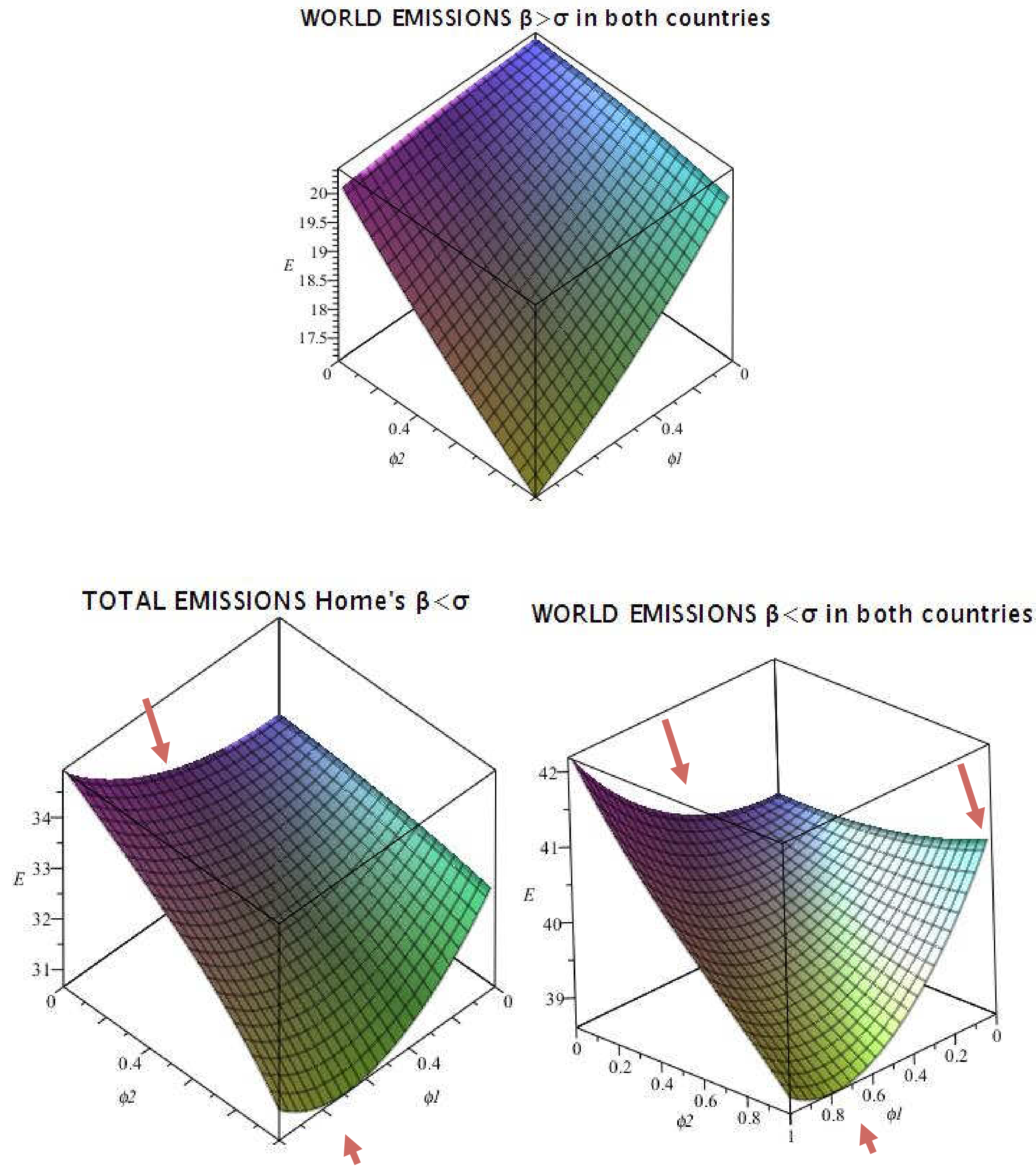
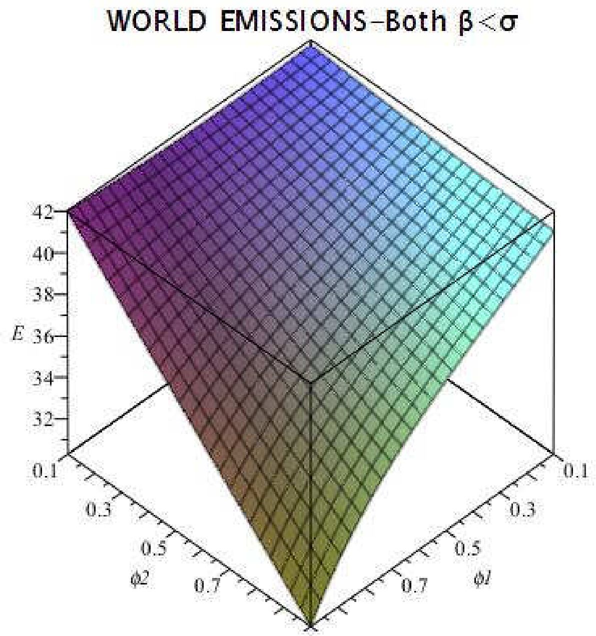


Fig. A1 *– Unilateral trade policy with different emission technologies: either both countries have clean technology (top), or Home only has dirty technology (middle), and both have dirty technology (right). The red arrows indicate where there could be scope for protectionist policies.*



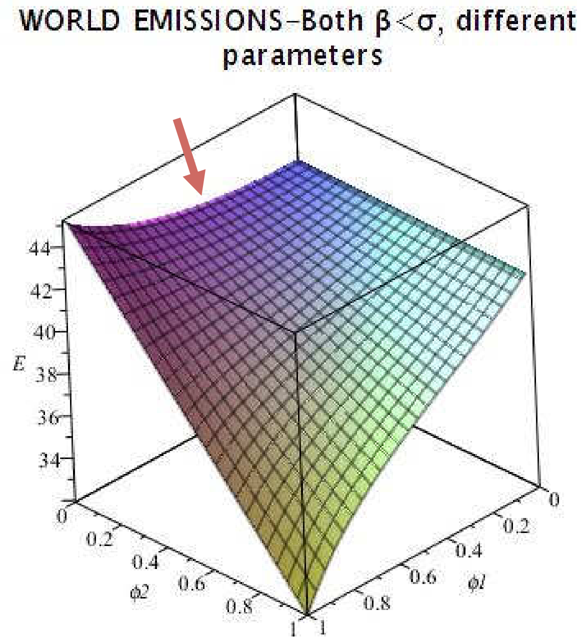


Fig. A2 *– Different production technologies and unilateral trade policies. Even when both countries have β < σ, the productivity difference can make trade environmentally friendly (left), but if the distribution of firms id too close, there can still be "leakages" (red arrows in right panel).*