Trade and the Environment with Heterogeneous Firms

Claustre Bajona and Andrea Pierce and Paul Missios

Ryerson University, Industry Canada, Ryerson University

24 September 2010

Trade and the Environment with Heterogeneous Firms

Claustre Bajona
Ryerson University

Paul Missios
Ryerson University

Andrea Pierce
Industry Canada

PRELIMINARY

September 24, 2010

Abstract

As the world is becoming more globalized and international trade agreements proliferate, there is a rising concern that trade liberalization may be detrimental to the environment. In a seminal paper Antweiler, Copeland, and Taylor (2001) identify three channels through which may trade affect the environment: Reducing trade barriers increases output (scale effect), abatement expenditures (technique effect), and changes the composition of goods produced (composition effect). All these channels operate at the country level and/or the industry levels. In this paper we focus on the effect that trade liberalization has on the pollution behavior of individual firms. We develop a theoretical framework that is able to account for differences in pollution behavior across firms within the same industry by embedding a model of trade with heterogeneous firms into the classical literature of trade and the environment following Antweiler, Copeland and Taylor (2001). The model shows that firm heterogeneity is important in determining the economy's aggregate behavior. In particular, more productive firms are less pollution intensive and are more likely to be exporters than low-productive firms. The model identifies a new channel through which trade affects the environment: a "selection effect". International trade causes the less productive firms within an industry to exit. Since less productive firms are more pollution intensive, through this channel international trade reduces pollution intensity by "selecting" these firms out of the industry.

1 Introduction

With the proliferation of international trade agreements and the continued integration of world markets, there is renewed interest in the effects of trade liberalization on the environment. Trade affects the environment through diverse and complicated channels that may partially offset each other. Identifying these channels is, therefore, crucial to better understand the relationship between trade liberalization and the environment. Most of the existent literature has documented channels that work at the country level or at the industry level, paying little attention to the individual firms that engage in international trade and that emit the pollution. Recent advances in the trade and industrial organization literatures have consistently shown that there are substantial differences between firms operating in any given industry (we call this fact "intra-industry firm heterogeneity"), and that these differences are crucial in determining the economic effects of trade liberalization.

In this paper, we develop a model that is able to account for differences in pollution behavior across firms, based on Melitz (2003) but adding firm pollution behavior following Copeland and Taylor (2003). We show that firm heterogeneity introduces a new important channel through which trade affects the environment which we label the "selection effect." In a closed economy setting we obtain that more productive firms have larger output, higher profits, lower pollution intensities and more abatement activity than less productive firms. Increases in the pollution tax rate increases prices and decrease outputs, firm pollution, aggregate pollution and pollution intensity. When opening up to trade, average productivity and profits increase as the least productive firms exit and the most productive firms grow to serve the new market. The remaining least productive firms produce only for the domestic market but will shrink and therefore pollute less than their autarky level. Surviving firms adjust their production and abatement such that their individual pollution intensity remains constant, but the change in the productivity distribution of the firms that remain in the market (caused by trade liberalization) decreases average (and aggregate) pollution intensity. While we do not refute the existence of the standard scale, composition, and technique effects of trade liberalization (see Antweiler et al., 2001), none of these can be said to completely encompass the reallocation of resources across firms within an industry which we demonstrate here. The nature of the firms which select export as a response to liberalization, relative to that of the firms that produce only for the domestic market or drop out of the market, generates an impact that is distinct from the industry output level, good specialization, and technique effects identify previously, which we label the "selection effect".

This paper contributes to three broad areas of research. First, it contributes to the fast growing literature on heterogeneous firms and trade by identifying a new area of analysis where firm heterogeneity is relevant. Second, it contributes to the environmental literature by systematically documenting the links between pollution behavior, export orientation, and individual firm's characteristics. Third, it contributes to the literature of trade and the environment by developing a new framework that takes into account firm heterogeneity and identifying a new channel through which trade affects the environment.

Initiated by Bernard and Jensen (1995), a large body of literature has emerged that uses census data to analyze the characteristics of individual firms which consistently finds that firms within any given industry differ substantially in almost all dimensions (Bernard et al., 2003, and Baldwin and Gu, 2006), including systematic differences between exporting and non-exporting firms within the same industry (e.g. Pavcnik, 2002; Bernard et al., 2007). In response to these findings, theoretical models have been developed to examine the role of firm heterogeneity in international trade, the most seminal being Eaton and Kortum (2003) and Melitz (2003). While different in assumptions regarding market structure, the two models find that trade liberalization affects different firms in different and contradictory ways. Trade liberalization introduces additional competition, driving the less productive firms in an industry out of the market and allowing the more productive firms in the same industry to expand and become exporters. This "selection mechanism" has important implications for a country's productivity gains from trade liberalization that cannot be accounted for if firm heterogeneity is not considered. We believe that this "selection" of firms that comes with trade liberalization may also have important consequences for the environment.

Some existing empirical studies report evidence suggesting that pollution behavior also differs across firms within an industry. Most of these studies tend to indicate that larger firms abate more and are less pollution intensive, although these studies are scarce and tend to be either at the aggregate level (comparing different industries) or for very specific industries. For example, Mazzanti and Zoboli (2009) find that more productive industries are less pollution intensive, Statistics Canada (2006) reports that larger businesses in Canada spend more (in per employee terms) in environmental protection, and Biehl and Klassen (2008) find some evidence that within the same industry larger firms spend more in pollution abating activities. Regarding emission intensity, Harrison and Antweiler (2003) find a negative relationship between a firm's size and its emissions per employee, while Shadbegian and Gray (2003) find that more productive firms have lower pollution intensity. One of the very few studies that look at the pollution abatement behavior of exporters and non-exporters is Holladay (2010). He measures the differences in behavior between exporters and non-exporters, finding that exporters generate less pollution than non-exporters after controlling for output values. His paper is mainly empirical and, even though he suggests that a model of pollution emissions and heterogeneous firms could deliver results consistent with his findings, he does not develop such a theoretical framework.

More recently, a few theoretical papers analyzing the effect of environmental policy in the presence of firm heterogeneity have emerged. Ergodan (2008), based on Eaton and Kortum (2003), and Li (2009) and Yokoo (2009), based on Melitz (2003), analyze the role of firm heterogeneity on the economic effects of environmental policy. These papers mainly concentrate on the analysis of environmental policy and do not focus on trade policy. The common assumption among these studies is that pollution emissions are proportional to the amount of inputs used and, therefore, even without incurring in any abatement costs more productive firms are less pollution intensive. In our paper, heterogeneity in pollution behavior emerges as a result of the model and is not be assumed ex-ante, allowing us to analyze how trade policy interacts with the source of heterogeneity in pollution behavior.

2 The model: closed economy

In this section we construct a model that analyzes firms' pollution behavior in an environment with firm heterogeneity. We extend the model in Melitz (2003) to account for pollution activity. Following Copeland and Taylor (2003), pollution is modeled as a byproduct of the production process. Firms have to pay a tax per each unit of pollution emitted, and have access to an abatement technology to reduce emissions.

2.1 Consumers

There are L identical consumers in the economy. Consumers life for an infinite number of periods. Time is discrete. Consumers derive utility from consumption of different varieties of a differentiated good and also from environmental quality. Pollution is harmful to consumers and therefore gives them negative utility. The period utility of a representative consumer is given by:

$$U = \left[\int_{\omega \in \Omega} c(\omega)^{\rho} \, d\omega \right]^{1/\rho} - h(Z) = C - h(Z) \tag{1}$$

where $c(\omega)$ is the amount consumed of good ω, $h(Z)$ is an increasing and convex function representing the disutility of pollution, and $0 < \rho < 1$ determines the elasticity of substitution between varieties, which is given by $\sigma = 1/(1-\rho)$.

There is no capital in the model and the consumption goods are not storable. Therefore, consumers solve a set of static problems, one per period. For simplicity, and given that we will consider only stationary equilibria, we omit time indices on the variables of the model.

Consumers are endowed with one unit of labor per period, which they supply inelastically, they own all firms in the economy, and receive all the pollution tax income. The demand of good ω by an individual consumer is given by:

$$c(\omega) = C\left(\frac{p(\omega)}{P}\right)^{-\sigma} \tag{2}$$

where C and P are consumption and price indices respectively, and are given by:

$$C = \left[\int_{\omega\in\Omega} c(\omega)^{\rho}\, d\omega\right]^{1/\rho} \tag{3}$$

and

$$P = \left[\int_{\omega\in\Omega} p(\omega)^{1-\sigma}\, d\omega\right]^{\frac{1}{1-\sigma}} \tag{4}$$

Notice that the consumer's budget constraint can be written as $PC = R/L$, where R is the economy's total expenditure.

2.2 Producers

The supply side is characterized by monopolistic competition. There is a continuum of firms, each producing a different variety ω of the differentiated good. Firms differ in their productivity levels, φ. Labor, l, is the only factor of production. There is a fixed cost of $f > 0$ units of labor associated with each period's production, which is the same across firms.

Following Copeland and Taylor (2003), we assume that the production process gives rise to two outputs- an amount q of the differentiated good, and pollution emissions z, which is proportional to output. Firms have access to an abatement technology that can reduce their emissions, which implies that emission intensity is a choice variable. In particular, firms can allocate a fraction θ of their labor input into abatement activities. If a firm chooses not to abate, each unit of output generates one unit of pollution. If a firm decides to abate, its level of output and emissions is given by [1]:

$$q(\omega) = \varphi(\omega)(1-\theta)l(\omega) \tag{5}$$

$$z(\omega) = \varphi(\omega)(1-\theta)^{1/\alpha}l(\omega) \tag{6}$$

where $0 < \alpha < 1$ indicates the industry's pollution intensity, and $\varphi(\omega)$ is the productivity level of the firm producing good ω. Rearranging these two equations we obtain the following joint production function:

$$q(\omega) = \varphi(\omega)^{1-\alpha}\, z(\omega)^{\alpha}\, l(\omega)^{1-\alpha} \tag{7}$$

Define $\phi = \varphi^{1-\alpha}$. Notice that any two firms with the same productivity parameter ϕ with behave in the same way. Therefore, in the rest of the paper we index firms by their productivity parameter ϕ instead of by the good that they are producing. The production function of a firm with productivity parameter ϕ is, thus, given by:

$$q(\phi) = \phi\, z(\phi)^{\alpha}\, l(\phi)^{1-\alpha} \tag{8}$$

With this formulation pollution, although a joint output, can be treated as an input.

Producers maximize profits taking into account that they are in a monopolistic competition setting and that they are too small to affect aggregate variables. Profits of a firm with productivity ϕ are given by:

$$\pi = p(q(\phi))\, q(\phi) - wl(\phi) - \tau z(\phi) - wf \tag{9}$$

where w indicates the wage and τ is the pollution tax rate, where $p(q(\phi))$ is derived from (**??**) using the fact that $q(\phi) = Lc(\phi)$.

Each firm faces the same residual demand with constant elasticity σ and hence charge the same profit maximizing markup over marginal cost. A firm with productivity ϕ will set a price,

$$p(\phi) = \frac{B}{\rho\phi} \tag{10}$$

[1] We adopt the same functional form for abatement as Copeland and Taylor (2003).

where

$$B = \frac{w^{1-\alpha}\tau^{\alpha}}{\alpha^{\alpha}(1-\alpha)^{1-\alpha}} \tag{11}$$

Defining $Q = LC$ as the total production index, revenue and profits can be written as:

$$r(\phi) = p(\phi)q(\phi) \ = P^{\sigma}Q\left(\frac{B}{\rho\phi}\right)^{1-\sigma} \ = R\left(\frac{B}{P\rho\phi}\right)^{1-\sigma} \tag{12}$$

and

$$\pi(\phi) = \frac{r(\phi)}{\sigma} - wf = \frac{R}{\sigma}\left(\frac{B}{P\rho\phi}\right)^{1-\sigma} - wf \tag{13}$$

where the second equalities use the fact that total revenue equals total income and $R = PQ$.

Pollution variables: Taking first order conditions on the producers' problem, we obtain total pollution emissions:

$$z(\phi) = \frac{w\alpha}{\tau(1-\alpha)}l(\phi) \tag{14}$$

Combining this equation with (**??**) and (**??**) we can write a firm's pollution level as a function of its revenue:

$$z(\phi) = \frac{\alpha}{\tau}\rho r(\phi) \tag{15}$$

Firm pollution intensity is then given by:

$$\frac{z(\phi)}{q(\phi)} = \left(\frac{\alpha}{1-\alpha}\frac{w}{\tau}\right)^{1-\alpha}\frac{1}{\phi} \tag{16}$$

Thus, holding the pollution tax rate constant, the pollution intensity of a firm depends on its productivity level, ϕ. As firms become more productive their pollution intensity decreases. As mentioned earlier, if a firm chooses not to abate then producing one unit of output leads to one unit of emissions and therefore $z(\phi)/q(\phi) = 1$. However, if abatement occurs then $z(\phi)/q(\phi) < 1$ which leads us to the corresponding abatement condition on productivity:

$$\phi > \left(\frac{\alpha}{1-\alpha}\frac{w}{\tau}\right) \equiv \bar{\phi} \tag{17}$$

Therefore only firms with productivity parameter $\phi > \bar{\phi}$ choose to operate the abatement technology. In what follows we assume that this conditions is not binding and, therefore, all firms operating in the market choose to abate.

We can derive the amount of labor devoted to abatement by combining (**??**) along with (**??**),

$$\theta(\phi) = 1 - \left(\frac{1}{\phi^{1/(1-\alpha)}} \frac{\alpha}{1-\alpha} \frac{w}{\tau} \right)^{\alpha} \tag{18}$$

Abatement activity is therefore increasing with productivity.

Firms decisions and productivity: Consider two firms with productivity parameters $\phi_1 > \phi_2$, then the relationship between their output, revenue, and profits is as follows:

$$\frac{q(\phi_1)}{q(\phi_2)} = \left(\frac{\phi_1}{\phi_2} \right)^{\sigma} \Rightarrow q(\phi_1) > q(\phi_2) \tag{19}$$

$$\frac{r(\phi_1)}{r(\phi_2)} = \left(\frac{\phi_1}{\phi_2} \right)^{\sigma-1} \Rightarrow r(\phi_1) > r(\phi_2) \tag{20}$$

$$\frac{\pi(\phi_1) - wf}{\pi(\phi_2) - wf} = \left(\frac{\phi_1}{\phi_2} \right)^{\sigma-1} \Rightarrow \pi(\phi_1) > \pi(\phi_2) \tag{21}$$

Therefore, as in Melitz (2003), more productive firms (higher ϕ) produce more, have higher revenues, earn higher profits, and charge a lower price than a less productive firms. Furthermore, the pollution, emission intensity, and abatement ratios relate in the following way:

$$\frac{z(\phi_1)}{z(\phi_2)} = \left(\frac{\phi_1}{\phi_2} \right)^{\sigma-1} \Rightarrow z(\phi_1) > z(\phi_2) \tag{22}$$

$$\frac{z(\phi_1)/q(\phi_1)}{z(\phi_2)/q(\phi_2)} = \frac{\phi_2}{\phi_1} \Rightarrow z(\phi_1)/q(\phi_1) < z(\phi_2)/q(\phi_2) \tag{23}$$

$$\frac{1 - \theta(\phi_1)}{1 - \theta(\phi_2)} = \left(\frac{\phi_2}{\phi_1} \right)^{\alpha/(1-\alpha)} \Rightarrow \theta(\phi_1) > \theta(\phi_2) \tag{24}$$

which state that more productive firms pollute more in absolute terms than less polluting firms (a result of producing more), but they also have lower pollution intensities and abate more.

2.3 Aggregation

Let M be the equilibrium mass of firms M (and therefore the mass of different varieties produced in the country) $\mu_{\phi}(\phi)$ be the equilibrium distribution of productivity levels of the plants that are in the market, with support in $(0, \infty)$. The aggregate price in (**??**) can be written as:

$$P = \left[\int_0^\infty p(\phi)^{1-\sigma} M \mu_\phi(\phi)\, d\phi \right]^{\frac{1}{1-\sigma}} \tag{25}$$

Similar to Melitz (2003), let us consider the following weighted average of firm productivity levels:

$$\widetilde{\phi} = \left[\int_0^\infty \phi^{\sigma-1} \mu_\phi(\phi)\, d\phi \right]^{\frac{1}{\sigma-1}} \tag{26}$$

Notice that this weighted average is independent of the number of firms M. Using the relationships (**??**)-(**??**), and following the techniques in Melitz (2003), the aggregate variables of the model can be written in terms of this productivity average as:

$$\begin{aligned} P &= M^{\frac{1}{1-\sigma}} p(\widetilde{\phi}), \qquad & Q &= M^{\frac{\sigma}{\sigma-1}} q(\widetilde{\phi}), \\ R &= M r(\widetilde{\phi}), \qquad & \Pi &= M \pi(\widetilde{\phi}), \\ Z &= M z(\widetilde{\phi}), \qquad & \frac{Z}{Q} &= M^{\frac{1}{1-\sigma}} \frac{z(\widetilde{\phi})}{q(\widetilde{\phi})} \end{aligned} \tag{27}$$

where $R = \int_0^\infty r(\phi) M \mu_\phi(\phi)\, d\phi$, $\Pi = \int_0^\infty \pi(\phi) M \mu_\phi(\phi)\, d\phi$ and $Z = \int_0^\infty z(\phi) M \mu_\phi(\phi)\, d\phi$ denote aggregate revenue, profit and pollution. Any industry with productivity distribution $\mu_\phi(\phi)$ and average productivity level $\widetilde{\phi}$ will lead to the same aggregate outcomes. Therefore, the aggregate variables of this model are equivalent to the aggregate variables of an economy with a mass M of identical firms with productivity levels $\widetilde{\phi}$.

2.4 Firm entry and exit

There is a large unbounded pool of potential entrants into the differentiated good's industry. Before entry, firms are identical and face uncertainty about their productivity. Each firm must make an initial investment f_e (measured in units of labor) to enter the market. Once the initial fixed cost is paid, the firm receives a productivity draw φ from a common distribution $G(\varphi)$ (and with density $g(\varphi)$). A firm's productivity remains fixed thereafter. Given the distribution of productivity levels across firms, we can derive the cumulative distribution and density of the productivity parameter $\phi = \varphi^{1-\alpha}$ as:

$$G_\phi(\phi) = G(\phi^{1/(1-\alpha)}) \tag{28}$$

$$g_\phi(\phi) = G'_\phi(\phi) = \frac{1}{1-\alpha} g(\phi^{1/(1-\alpha)}) \phi^{\alpha/(1-\alpha)} \tag{29}$$

Upon entry, if its productivity draw is too low a firm may decide to not produce and exit the market. If the firm does produce then each period there is a probability δ that the firm will be forced to exit due to an exogenous shock. Like Melitz (2003) we only consider stationary equilibria (in which the aggregate variables remain constant over time). In a stationary equilibrium, each firm's per period profit will remain constant over time, as long as it is allowed to stay in the market. Assuming that there is no time discounting, the expected value of a firm is given by

$$v(\phi) = \max\left\{0, \sum_{t=0}^{\infty}(1-\delta)^t \pi(\phi)\right\} = \max\left\{0, \frac{1}{\delta}\pi(\phi)\right\} \tag{30}$$

Therefore, once a firm has received its productivity draw, it will stay in the market and produce only if it earns positive profits each period. Define the productivity cutoff of survival, ϕ^*, as the productivity parameter of a firm that makes zero period profits in equilibrium: $\pi(\phi^*) = 0$. Any firm with a productivity parameter below ϕ^* immediately exits the market and never produces. All firms with productivity parameters above ϕ^* stay in the market and produce. Therefore, the productivity distribution of the firms that stay in the market can be written as a function of the productivity distribution and the productivity cutoff in the following way:

$$\mu_\phi(\phi) = \begin{cases} \frac{g_\phi(\phi)}{p_{in}} & \text{if } \phi \geq \phi^* \\ 0 & \text{otherwise} \end{cases} \tag{31}$$

where $p_{in} = 1 - G_\phi(\phi^*)$ be the ex-ante probability of successful entry. The aggregate productivity level $\widetilde{\phi}$ can also be written as a fuction of the cutoff level ϕ^*:

$$\widetilde{\phi}(\phi^*) = \left[\frac{1}{p_{in}} \int_{\phi^*}^{\infty} \phi^{\sigma-1} g(\phi) d\phi\right]^{\frac{1}{\sigma-1}} \tag{32}$$

The assumption that $\widetilde{\phi}$ is finite, imposes that the $(\sigma-1)$th uncentered moment of $g_\phi(\phi)$ must be finite. We can see from (**??**) that the average productivity level $\widetilde{\phi}$ is completely determined by the cutoff productivity level ϕ^*. Letting $\bar{r} = R/M$ and $\bar{\pi} = \Pi/M$ be average revenue and profit per firm, we can expressed them as a function of the cutoff level (using (**??**):

$$\bar{r} = r(\widetilde{\phi}) = \left(\frac{\widetilde{\phi}(\phi^*)}{\phi^*}\right)^{\sigma-1} r(\phi^*), \qquad \bar{\pi} = \left(\frac{\widetilde{\phi}(\phi^*)}{\phi^*}\right)^{\sigma-1} \frac{r(\phi^*)}{\sigma} - wf \tag{33}$$

Zero cutoff profit condition: Using (**??**), (**??**) and $\pi(\phi^*) = 0$ we can now derive the zero cutoff profit condition that needs to be satisfied in equilibrium:

$$\pi(\phi^*) = 0 \iff r(\phi^*) = \sigma w f \iff \bar{\pi} = w f k(\phi^*) \tag{34}$$

where $k(\phi^*) = [\widetilde{\phi}(\phi^*)/\phi^*]^{\sigma-1} - 1$.

Free entry condition: Prior to entry, firms will consider paying the fixed investment only if expected future profits are weakly positive. A firm's net value of entry is given by:

$$v_e = p_{in}\bar{v} - w f_e = \frac{1 - G_\phi(\phi^*)}{\delta}\bar{\pi} - w f_e \tag{35}$$

where $\bar{v}$ denotes the present value of profit: $\bar{v} = \sum_{t=0}^{\infty}(1-\delta)^t\bar{\pi}$ as well as the average value of firms, conditional on successful entry: $\bar{v} = \int_{\phi^*}^{\infty} v(\phi)\mu(\phi)d\phi$. In equilibrium, $v_e = 0$ and the free entry condition becomes:

$$\bar{\pi} = \frac{\delta w f_e}{1 - G_\phi(\phi^*)} \tag{36}$$

2.5 Equilibrium in a closed economy

The resolution of the model follows the same techniques as Melitz (2003). The zero cutoff profit condition (ZCP) (**??**) and free entry condition (FE) (**??**), together with the expression for average productivity (**??**) determine a system of two equations and two unknowns, $\bar{\pi}$ and ϕ^*. Figure 1 plots these two conditions in (ϕ, π) space. The proof for the existence of a unique equilibrium is identical to Melitz (2003) and we do not repeat it here.

Notice that (**??**) and (**??**) do not depend on τ and, therefore, the productivity threshold ϕ^*, the average productivity $\widetilde{\phi}$, and the profits of the average firm $\bar{\pi}$ do not change with the pollution tax rate.

Additional equilibrium conditions include stationarity in the mass of firms operating in the market as well as labor market clearing conditions. Stationarity requires that in every period the mass of successful entrants, $p_{in}M_e$ exactly equals the mass of firms who exit because of a negative exogenous shock, δM. Thus, in a stable equilibrium the mass of new entrants will be defined by:

$$M_e = \frac{\delta M}{1 - G_\phi(\phi^*)} \tag{37}$$

Let L_e define the initial fixed investment (measured in units of labor) made by the potential entrants. The labor market clearing conditions implies that:

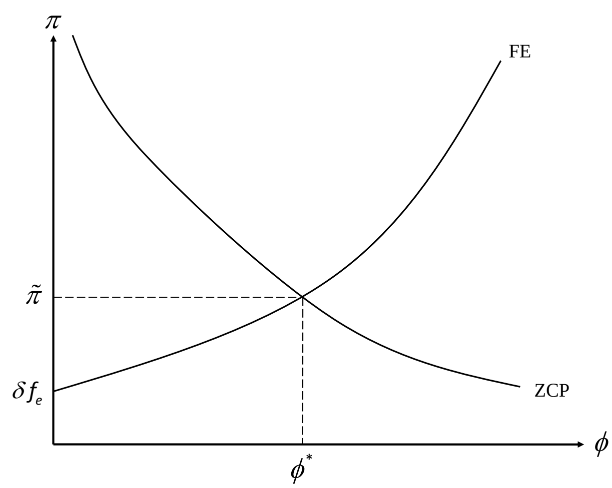

Figure 1: ZCP and FE determining equilibrium cutoff and average profit

$$L = L_p + L_e + Mf \tag{38}$$

where L_p represents aggregate labor hired by the firms, net of fixed costs, and Mf represents the fixed costs payed by the total mass of firms, and $L_e = M_e f_e$ is the amount of labor used to pay the entry cost. Combining these conditions with the following expression for aggregate profits:

$$\Pi = R - \frac{w}{1-\alpha} L_p - wMf \tag{39}$$

we obtain the equilibrium total revenue:

$$R = \frac{wL}{1-\alpha\rho} \tag{40}$$

Notice that total revenue does not depend on the pollution tax rate and, after normalizing the wage rate to 1, it is a function of the country size L and parameter values. Other equilibrium variables that do not depend on the pollution tax rate are:

$$L_p = \frac{(1-\alpha)\rho}{w} R \tag{41}$$

$$M = \frac{R}{\sigma(\bar{\pi} + wf)} \tag{42}$$

$$L_e = \frac{\bar{\pi} M}{w} \tag{43}$$

$$M_e = \frac{L_e}{f_e} \tag{44}$$

By using (**??**), (), and (**??**) for $\phi = \widetilde{\phi}$, we can write the price index and the aggregate quantity as functions of the productivity threshold ϕ^* only:

$$P = \left(\frac{1}{\sigma f} \frac{L}{1 - \alpha\rho}\right)^{1/(1-\sigma)} \frac{B}{\rho\phi^*} \tag{45}$$

$$Q = \frac{wL}{1 - \alpha\rho} \left(\frac{1}{\sigma f} \frac{L}{1 - \alpha\rho}\right)^{1/(\sigma-1)} \frac{\rho\phi^*}{B} \tag{46}$$

Finally, total aggregate pollution and total pollution per unit of output can be expressed as:

$$Z = \frac{\rho\alpha}{\tau} R = \frac{\rho\alpha}{\tau} \frac{wL}{1 - \alpha\rho} \tag{47}$$

and

$$\frac{Z}{Q} = \frac{\rho\alpha}{\tau} P = \frac{1}{\phi^*} \left(\frac{1}{\sigma f} \frac{L}{1 - \alpha\rho}\right)^{1/(1-\sigma)} \left(\frac{w\alpha}{\tau(1 - \alpha)}\right)^{1-\alpha} \tag{48}$$

Notice that aggregate pollution intensity depends negatively on both the pollution tax rate and the average productivity parameter. Therefore, the higher the average productivity of firms in the market, the lower the aggregate pollution intensity.

Welfare: The welfare of an individual consumer in equilibrium is given by the value of his utility at the equilibrium values, and it is given by:

$$W = \frac{Q}{L} - h(Z) = \frac{R}{PL} - h(Z) \tag{49}$$

Using the equilibrium expressions for R and P, we obtain:

$$W = \frac{Q}{L} - h(Z) = \frac{w}{1 - \alpha\rho} \left(\frac{1}{\sigma f} \frac{L}{1 - \alpha\rho}\right)^{1/(\sigma-1)} \frac{\rho\phi^*}{B} \tag{50}$$

It is important to notice that only the first term in the welfare function depends on the average productivity parameter.

2.6 Equilibrium values and the pollution tax rate

In this section we analyze how changes in the pollution tax rate affect the equilibrium variables. From the derivations on the previous section we observe that aggregate revenue R, the productivity threshold, ϕ^*, the average profits, $\bar{\pi}$ and, therefore, the total mass of varieties produced, M, do not depend on the pollution tax rate. The main variables of interest that are affected by the pollution tax rate are prices, quantities produced, and pollution emissions, all at both the firm and the aggregate level, as well as welfare.

Differentiating the equilibrium expressions for prices and quantities with respect to τ we obtain:

$$\frac{dP}{d\tau} = \frac{\alpha}{\tau} P > 0 \tag{51}$$

$$\frac{dQ}{d\tau} = -\frac{\alpha}{\tau} Q < 0 \tag{52}$$

Notice that an increase in the pollution tax rate increases the aggregate price and decreases aggregate output in the same proportion. This result is a result of the specification of the model, which makes total revenue R a function of modeling parameters and the country's population L. The effects at the firm level are given by:

$$\frac{dp(\phi)}{d\tau} = \frac{\alpha}{\tau} p(\phi) > 0 \tag{53}$$

$$\frac{dq(\phi)}{d\tau} = -\frac{\alpha}{\tau} q(\phi) < 0 \tag{54}$$

Therefore, as for the aggregate variables, firm level revenue $r(\phi)$ does not change with the pollution tax rate.

The effect of changes in the pollution tax rates of emission-related variables is as follows:

$$\frac{dz(\phi)}{d\tau} = -\frac{z(\phi)}{\tau} < 0 \tag{55}$$

$$\frac{d(z(\phi)/q(\phi))}{d\tau} = -\frac{1-\alpha}{\tau} \frac{z(\phi)}{q(\phi)} < 0 \tag{56}$$

As expected, an increase in pollution taxes causes firms to pollute less (and abate more). The decrease in pollution emissions is higher than the reduction in output, reducing emissions per unit of output. Given that pollution taxes do not affect the mass of firms in the market or its productivity distribution, the effect on aggregate variables mimics the effect on firm level variables:

$$\frac{dZ}{d\tau} = -\frac{Z}{\tau} < 0 \tag{57}$$

$$\frac{d(Z/Q)}{d\tau} = -\frac{1-\alpha}{\tau}\frac{Z}{Q} < 0 \tag{58}$$

The intuition for these effects is the following: as pollution taxes increase, more resources are devoted to abatement, reducing pollution intensity (technique effect). Furthermore, less resources are devoted to the production of output, so output decreases, reducing pollution emissions even more (scale effect).

The effect of an increase in pollution taxes on welfare is given by:

$$\frac{dW}{d\tau} = \frac{\alpha}{\tau}R\left(\frac{h'(Z)\rho}{\tau} - \frac{1}{PL}\right) \tag{59}$$

Therefore, an increase in the pollution tax increases welfare if and only if:

$$h'(Z) > \frac{\tau}{\rho PL} \tag{60}$$

Using (**??**) and the expression for P as function of ϕ^*, this inequality can be written as:

$$h'\left(\frac{\alpha\rho R}{\tau}\right) > D\phi^*\tau^{1-\alpha} \tag{61}$$

where D is a positive constant that does not depend on τ. The left hand side of this equation is decreasing in τ, given our assumption that h is convex, and the right hand side is increasing in τ. It is easy to see that there exists a unique $\hat{\tau} > 0$ that maximizes welfare. Welfare increases with the pollution tax for values of τ below $\hat{\tau}$ and it decreases with the tax for values above this threshold.

In this paper we have assumed that all firms use the abatement technology. Therefore, we have implicitly assumed that:

$$\tau > \frac{\alpha}{1-\alpha}\frac{1}{(\phi^*)^{1/(1-\alpha)}} = \tau_{min} \tag{62}$$

3 Open economy model: symmetric world

There are $n + 1$, $n \geq 1$ identical countries in the world, that look like the economy described in the previous section and which are allowed to trade with each other. This symmetry assumption, which is made for simplicity, implies that the pollution tax rates and the size of the population are the same across countries. Therefore, all firms with a given productivity parameter ϕ will behave in the same way in all countries, and we can omit country indicators.

Firms that decide to export their product to other countries incur in two additional costs: (i) a per-unit iceberg trade cost which requires the shipment of $\gamma > 1$ units of good per each unit that is sold in a foreign country and (ii) a fixed cost of entering the export market, f_{ex}. We assume that firms pay for this fixed cost with equal installments per period, which translates into a period fixed cost of $f_x = \delta f_{ex}$. We assume that $\gamma^{\sigma-1} f_x > f$, which will ensure that not all firms become exporters. These additional costs of exporting will cause firms to set different prices in the domestic and the export markets. In particular, the price that firms will charge in the domestic market is the same as in the closed economy:

$$p_d(\phi) = \frac{B}{\rho\phi} \tag{63}$$

The price set for the foreign market reflects the variable trade costs, and is equal to:

$$p_d(\phi) = \frac{B\gamma}{\rho\phi} \tag{64}$$

Using (**??**), we can write the equilibrium revenue obtained in each market as:

$$r_d(\phi) = R\left(\frac{P\rho\phi}{B}\right)^{\sigma-1} \tag{65}$$

for the domestic market, and:

$$r_x(\phi) = R\left(\frac{P\rho\phi}{B\gamma}\right)^{\sigma-1} = \gamma^{1-\sigma} r_d(\phi) \tag{66}$$

for the foreign markets. Notice that since the revenue in the exporting markets is smaller than the revenue from sales in the domestic market, and since entering the export market requires the payment of an additional fixed cost, any exporting firm will find it profitable to produce for the domestic market also. Our modeling assumptions, thus, rule out the possibility of firms that export 100 percent of their output. Furthermore, if a firm exports at all, it will supply all foreign countries.

The total revenue of any firm can be written as:

$$r(\phi) = \begin{cases} r_d(\phi) & \text{if firm does not export} \\ r_d(\phi) + n r_x(\phi) = (1 + n\gamma^{1-\sigma}) r_d(\phi) & \text{if firm exports} \end{cases} \tag{67}$$

3.1 Firm Entry, exit and export status

Firms will enter the export market only if the net profits from exporting are positive. Profits, like revenues, depend on export status. Letting $\pi_d(\phi)$ be profits earned from domestic sales and $\pi_x(\phi)$ be profits generated from exporting, we obtain:

$$\pi_d(\phi) = \frac{r_d(\phi)}{\sigma} - wf, \qquad \pi_x(\phi) = \frac{r_x(\phi)}{\sigma} - wf_x = \frac{\gamma^{1-\sigma} r_d(\phi)}{\sigma} - wf_x \tag{68}$$

Defining combined per period profits as $\pi(\phi) = \pi_d(\phi) + max\{0, n\pi_x(\phi)\}$, the value of a firm is $v(\phi) = max\{0, \pi(\phi)/\delta\}$. Let ϕ_x^* be such that $\pi_x(\phi^*) = 0$. Given that profits are increasing in ϕ, only firms with productivity parameter $\phi > \phi_x^*$ export. As in the closed economy case, let ϕ^* be such that $\pi_d(\phi^*) = 0$. Only firms that draw a productivity level such that $\phi > \phi^*$ will stay the market. Given our assumption of $\gamma^{\sigma-1} f_x > f$,it is the case that $\phi_x^* > \phi$ and not all firms are active in the export market.

As in the closed case, the equilibrium distribution of productivity levels, $\mu_\phi(\phi)$ is determined by the ex-ante distribution of productivity levels. Additionally, $p_{in} = 1 - G_\phi(\phi^*)$ is the ex-ante probability of successful entry and the ex-ante probability of exporting is given by:

$$p_x = \frac{1 - G_\phi(\phi_x^*)}{1 - G_\phi(\phi^*)} \tag{69}$$

Notice that p_x also represents the fraction of firms that export. If M is the equilibrium mass of firms in a country, then $p_x M$ represents the fraction of exporting firms. Thus the total mass of firms supplying in any country would be $M_T = M(1 + np_x)$ (which also equals the total variety of goods available in any country).

3.2 Aggregation

Using the weighted average function defined earlier in (**??**) and the market share as weights, similar to Melitz (2003), we can define the average productivity of domestic and foreign firms competing in a single country:

$$\widetilde{\phi}_T = \left\{ \frac{1}{M_T} \left[M\widetilde{\phi}^{\sigma-1} + nM_x(\gamma^{-1}\widetilde{\phi}_x)^{\sigma-1} \right] \right\}^{\frac{1}{\sigma-1}} \tag{70}$$

We can then solve for aggregate equilibrium variables as functions of total productivity average and the total mass of competing firms:

$$P = M_T^{\frac{1}{1-\sigma}} p(\widetilde{\phi}_T) = M_T^{\frac{1}{1-\sigma}} \frac{B}{\rho\widetilde{\phi}_T} \tag{71}$$

$$R = M_T r_d(\widetilde{\phi_T}) \tag{72}$$

$$Z = M_T z(\widetilde{\phi_T}) \tag{73}$$

Average expected revenue and profits generated from both domestic and export sales, across all domestic firms in a country become:

$$\bar{r} = r_d(\widetilde{\phi}) + p_x n r_x(\widetilde{\phi}_x), \qquad \bar{\pi} = \pi_d(\widetilde{\phi}) + p_x n \pi_x(\widetilde{\phi}_x) \tag{74}$$

3.3 Equilibrium conditions of an open economy

The set of equations that characterize the stationary equilibrium of the open economy includes two zero profit cutoff conditions:

$$\pi_d(\phi^*) = 0 \quad \Longleftrightarrow \quad \pi_d(\widetilde{\phi}) = fk(\phi^*) \tag{75}$$

$$\pi_x(\phi_x^*) = 0 \quad \Longleftrightarrow \quad \pi_x(\widetilde{\phi}_x) = f_x k(\phi_x^*) \tag{76}$$

where $k(\phi) = [\widetilde{\phi}(\phi)/\phi]^{\sigma-1} - 1$. Solving the above conditions for revenues and using the property in (**??**), we can derive $\widetilde{\phi}_x$ as a function of ϕ^*:

$$\frac{r_x(\phi_x^*)}{r_d(\phi^*)} = \gamma^{1-\sigma}\left(\frac{\phi_x^*}{\phi^*}\right)^{\sigma-1} = \frac{f_x}{f} \quad \Longleftrightarrow \quad \phi_x^* = \gamma\left(\frac{f_x}{f}\right)^{\frac{1}{\sigma-1}} \phi^* \tag{77}$$

Using (**??**) we can define the zero profit condition for the open economy by expressing average profit $\bar{\pi}$ as a function of the cutoff level ϕ^*:

$$\begin{aligned} \bar{\pi} &= \pi_d(\widetilde{\phi}) + p_x n \pi_x(\widetilde{\phi}_x) \\ &= fk(\phi^*) + p_x n f_x k(\phi_x^*) \end{aligned} \tag{78}$$

where using (**??**), ϕ_x^* and thus p_x are implicit functions of ϕ^*.

The equations for the present value of average profits and net value entry are the same as in the closed economy's case. Therefore the free entry condition remains the same as in the closed economy. From conditions (**??**), (**??**), and (**??**), we obtain the equilibrium values of $\bar{\pi}$, and productivity thresholds ϕ^*, and ϕ_x^*. Also, like in the closed economy case, these variables are independent of the pollution tax rate.

Additionally, since we are still assuming a stationary equilibrium, the aggregate stability condition and labor market clearing condition remain unchanged. Following the same strategy as in the closed economy, average firm revenue can be written as

$$\bar{r} = r_d(\widetilde{\phi}) + p_x n r_x(\bar{\phi}_x) = \sigma(\bar{\pi} + wf + p_x n w f_x). \tag{79}$$

Therefore the mass of firms operating in a given country becomes:

$$M = \frac{R}{\bar{r}} = \frac{wL}{(1-\alpha\rho)\sigma(\bar{\pi} + wf + p_x nwf_x)} \tag{80}$$

3.4 Effects of trade liberalization

To see the effects of trade liberalization, we compare the steady state equilibrium values under trade and autarky. Let us denote ϕ_a^* and $\widetilde{\phi}_a$ as the cutoff and average profit levels in autarky, and use the notations in the previous section to denote variables in the open economy. As we have already noted, the FE condition does not change under trade and therefore the FE curve remains the same. However, after comparing (**??**) and (**??**) we can see that the trade leads to the ZCP curve shifting upwards. It thus follows that the cutoff productivity level of production and the average profit per firm increases with trade. Thus, $\phi^* > \phi_a^*$ and $\bar{\pi} > \bar{\pi}_a$ as shown in Figure 2.

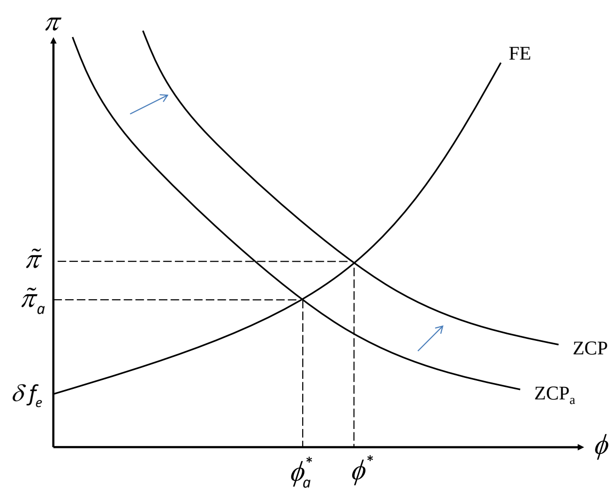

Figure 2: Effects of trade on equilibrium cutoff and average profit

Now firms with productivity between ϕ_a^* and ϕ^* are forced to exit the market because they no longer earn positive profits. Note that this is consistent with the empirical findings of Bernard et al (1999) and Pavcnik (2002), who find that trade forces the least productive firms to exit. Comparing the equilibrium mass of firms under autarky and trade (see (**??**) and (**??**)), reveals that $M_a > M$, where M_a is the number of firms under autarky. Although the number of domestic firms decreases after trade, consumers are better off because the increase in available variety ($M_T = (1 + np_x)M > M_a$).

Investigating individual firm profit, revenue allows us to determine the effect of trade on firm performance. Supposing that a firm has productivity level $\phi > \phi^*$, and let $r_a(\phi) > 0$ denotes the firm's revenue in autarky. Following Melitz (2003), the revenues that this firm obtains before and after trade are ranked in the following way:

$$r_d(\phi) < r_a(\phi) < r_d(\phi) + nr_x(\phi) \tag{81}$$

This implies that once opening to trade, all firms will lose some domestic market share. Firms that only sell domestically will incur a total revenue loss ($r_d(\phi) < r_a(\phi)$). Firms that do export derive additional profit from the export sales. However, there are some exporting firms whose additional profits do not make up for the loss in domestic market profits, and therefore lose from trade. It is only the most productive firms who increase both their market share and their profits (See Figure 3 and 4)

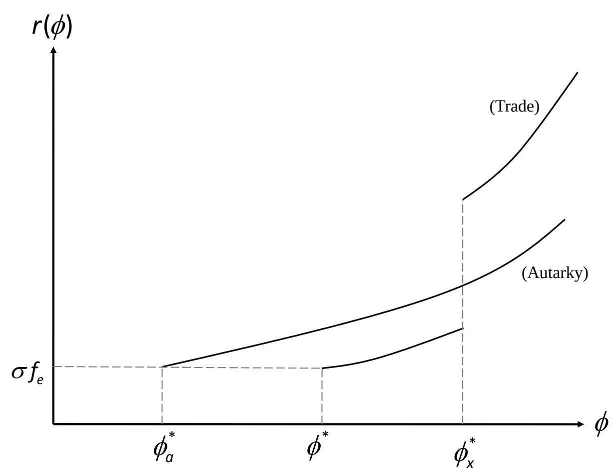

Figure 3: The reallocation of market shares

Trade also results in resource reallocation. The existing, highly productive firms who gain market share after trade want to expand their production and therefore hire more labor. This excess labor demand increases the real wage (w/P), forcing the least productive firms to be shut down. This leads to an increase aggregate productivity as the most productive firms expand and the least productive firms contract and exit.

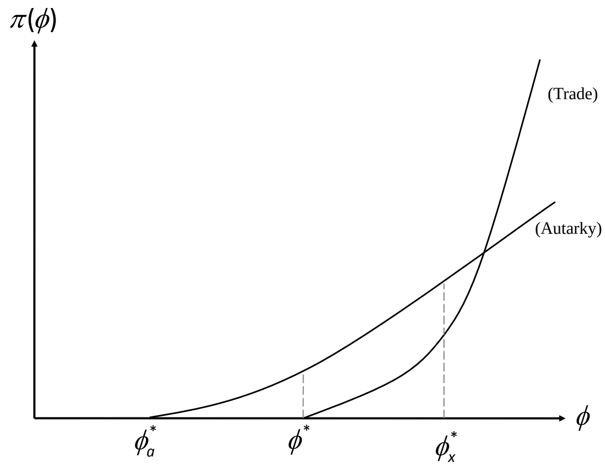

Figure 4: The reallocation of profits

3.5 Trade and pollution variables

We can now address how firm and aggregate pollution performance changes with trade. Recalling the expression for pollution as a function of revenue, (**??**), we see that holding the pollution tax rate constant, firm level pollution will have the same properties as revenue. Thus using (**??**) we obtain:

$$z_d(\phi) < z_a < z_d(\phi) + nz_x(\phi) \tag{82}$$

Therefore, after opening to trade, those firms who are only active in the domestic market emit less pollution when the economy is open to trade than under autarky. However those firms who produce for domestic and foreign markets pollute more, in absolute terms, than their autarky level.

To get an accurate measure of pollution performance, we need to compare firm and aggregate pollution intensities before and after trade. In equation (**??**) we found pollution intensity to be:

$$\frac{z(\phi)}{q(\phi)} = \left(\frac{\alpha}{1-\alpha}\frac{w}{\tau}\right)^{1-\alpha}\frac{1}{\phi} \tag{83}$$

Thus, holding the pollution tax rate constant, a firms pollution intensity depends only on its productivity ϕ. Therefore, since individual firm productivity does not change after opening up to trade, a firm's pollution intensity remains unchanged as well. This result does not hold, however, when we consider the pollution intensity of the "average" firm:

$$\frac{z(\widetilde{\phi_T})}{q(\widetilde{\phi_T})} = \left(\frac{\alpha}{1-\alpha}\frac{1}{\tau}\right)^{1-\alpha} \frac{1}{\widetilde{\phi_T}} \tag{84}$$

Given that the average productivity has increased, that is $\widetilde{\phi_T} > \widetilde{\phi_a}$, the average firm has lower pollution intensity. Therefore, any individual firm that operates under both autarky and free trade emits the same pollution per unit of output under both regimes (there is no "technique effect"). However, since trade forces the less productive (and highly polluting) firms to exit the market, on average pollution intensity is lower under trade than under autarky.

Aggregate pollution variables follow a similar pattern. Their mathematical expressions are identical to the ones for the closed economy. Aggregate pollution equals:

$$Z = \frac{\alpha\rho R}{\tau} \tag{85}$$

where $R = wL/(1 - \alpha\rho)$, and aggregate pollution intensity can be expressed as:

$$\frac{Z}{Q} = \left(\frac{R}{w\sigma f}\right)^{1/(1-\sigma)} \frac{\alpha B}{\tau\phi^*} \tag{86}$$

Using the expression of P as a function of ϕ^* we obtain:

$$\frac{Z}{Q} = \frac{M^{1/(1-\alpha)}}{\phi^*}\left(\frac{\alpha}{\tau(1-\alpha)}\right)^{1-\alpha} \tag{87}$$

which is decreasing in the productivity cutoff. Given that $\phi^* > \phi_a^*$, trade leads to a reduction in aggregate pollution intensity. In this framework, more productive firms abate more and have lower pollution intensity. By reallocating resources towards more productive firms, trade also reallocates resources towards less pollution intensive firms, reducing overall pollution intensity. This is an additional mechanism in which trade affects pollution, which we label a "selection effect". Notice that in this model there is no "technique effect" at the firm level, since the abatement behavior of firms does not change in the open economy equilibrium. The aggregate result, though, is the same that we would obtain under the technique effect.

3.6 Optimal pollution tax rate

Recalling the expression of welfare in equilibrium, (**??**):

$$W = \frac{w}{1-\alpha\rho}\left(\frac{1}{\sigma f}\frac{L}{1-\alpha\rho}\right)^{1/(\sigma-1)}\frac{\rho\phi^*}{B} - h\left(\frac{\alpha\rho w L}{\tau(1-\alpha\rho)}\right) \tag{88}$$

It is easy to see that this function is increasing in the productivity cutoff ϕ^*. Therefore, since this cutoff is higher in the open economy, we obtain that welfare increases after opening to trade. There are two channels in which trade affects welfare. First, although there are fewer domestic firms in the market after trade, the number of varieties available to the consumer increases due to imports. Second, there is an increase in efficiency due to the higher average productivity in the country.

The optimal pollution tax rate also changes after opening to trade. Differentiating the equation above with respect to τ, and equating it to zero we obtain that the optimal pollution tax rate satisfies:

$$h'\left(\frac{\alpha\rho R}{\tau}\right) = D\phi^*\tau^{1-\alpha} \tag{89}$$

For any given τ, the left hand side of this equation is the same under the autarky and trade equilibria, since R does not change. The right hand side of the equation is higher under trade, since $\phi^* > \phi_a^*$. Therefore, the optimal pollution tax rate will be smaller under trade. The intuition for this result is as follows: under trade the average firm abates more than under autarky, so more resources are devoted to abatement and less to production. At any given pollution tax, pollution intensity is lower under trade. In particular, at the optimal pollution tax for the closed economy, pollution intensity under trade is below its welfare-maximizing value. Therefore, lowering the pollution tax at the margin increases welfare.

4 Conclusion

This paper analyzes the effect of trade on pollution intensity in an environment in which firms are heterogeneous in their productivity levels. In this framework, firms abatement decisions are endogenous. We identify an additional channel through which trade affects the environment: a "selection effect", which is different from the "technique" effect identified by Copeland and Taylor (2003) but that it is empirically equivalent when looking only at aggregate variables or averages.

In our framework, more productive choose to abate more per unit of output. International trade concentrates production resources into more productive firms, increasing the average productivity of the firms in the market. More productive (and less pollution intensive) firms expand and less productive (and more pollution intensive firms) leave the market or contract. As a result, aggregate pollution intensity decreases while overall pollution levels stay the same. Furthermore, individual firms do not change their abatement decisions compared to the autarkic case.

5 References

Antweiler, Werner, B. Copeland and M. S. Taylor. (2001). "Is free trade good for the environment?" American Economic Review. 91, 877-908.

Baldwin, J. R. and W. Gu (2006). "The Impact of Trade on Plant-Scale, Production Run Length, and Diversification," Analytical Studies Research Paper Series, catalog number 11F0027MIE No. 027, Ottawa: Statistics Canada.

Bernard, A. B., and J. B. Jensen (1995). "Exporters, Jobs, and Wages in U.S. Manufacturing, 1976-1987," Brookings Papers on Economic Activity, Microeconomics, 67-119.

Bernard, A., Jensen B., S. Redding S., and Schott P. (2007). "Firms in International Trade," Journal of Economic Perspectives, 21, 105-130.

Copeland, T. and M. S. Taylor. (2003). "Trade and the Environment: Theory and evidence." Princeton University Press, Princeton.

Eaton, J. and S. S. Kortum (2002). "Technology, Geography and Trade," Econometrica 70, 1741-79.

Ergodan, A. M. (2008). "Environmental Regulations and Bilateral Manufacturing Trade: The Case of OECD Countries," Mimeo, University of Minnesota.

Holladay, J. S. (2010). "Are Exporters Mother Nature's Best Friends?" Mimeo. Available at SSRN: http://ssrn.com/abstract=1292885

Klassen, R.D. and M. Biehl (2008). "Building the Business Case for Sustainable Manufacturing: Linking Green and Lean Management to Performance," Industry Canada, Policy and Sector Service Branch.

Li, Z. (2008). "Productivity Dispersion across Plants, Emission Abatement and Environmental Policy". Department of Economics, University of Toronto, Toronto.

Mazzanti, M., Zoboli, R. (2009). "Environmental E?ciency and Labour Productivity: Trade-o? or joint dynamics? A theoretical investigation and empirical evidence from Italy using NAMEA". Ecological Economics, 68, 1182-1194.

Melitz, M. (2003). "The Impact of Trade on Intra-Industry Reallocations and Aggregate Industry Productivity," Econometrica, 71, 1695-1726.

Pavcnik, N. (2002). "Trade Liberalization, Exit, and Productivity Improvements: Evidence from Chilean Plants". The Review of Economic Studies, 69, No. 1, 245-276.

Shadbegian, R. J. and W. B. Gray (2003). "What Determines Environmental Performance at Paper Mills? The Roles of Abatement Expenditures, Regulation, and Efficiency," Topics on Economic Analysis and Policy 3(15).

Statistics Canada (2006). "Environmental Protection Expenditures in the Business Sector," Environment Accounts and Statistics Division, System of National Accounts, catalogue no.16F0006X. Ottawa.

Yokoo, H. (2009). "Heterogeneous Firms, the Porter Hypothesis and Trade". Institute of Economic Research Kyoto University, Japan.