Trade, Emissions, and Regulatory (Non-)Compliance: Implications for Firm Heterogeneity

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Abstract: This paper provides implications of firm heterogeneity for global pollution and trade liberalization in a model of endogenous markups and non-compliance with environmental regulations. We show that firms with heterogeneous productivities respond differently to a uniform environmental regulation, which changes the market competition structure within a country and across countries, and disentangles the interaction effects of environmental regulations and trade liberalization. In autarky, efficient firms are favored by environmental regulations but they may produce more emissions via the non-compliance to escape the regulation and maintain their competitiveness. In a symmetric two-country open economy, trade liberalization can break the output-environment trade-off, not only increasing the world-wide output but also decreasing global pollution emissions. Under asymmetric environmental regulations, a unilateral increase in the emission tax decreases the average productivity in this country if openness to trade is substantially high, which contrasts with the effect under autarky whereby the average productivity increases with the emission tax. Our welfare analysis shows that there exists a U-shaped relationship between the optimal emission tax and openness to trade regardless of whether under tax harmonization or tax competition. Trade liberalization unambiguously decreases global pollution emissions under tax harmonization but it may increase global pollution emissions under tax competition.

JEL Classification: F12, F18, Q56, R13.

Keywords: Firm heterogeneity, environmental regulation, trade liberalization, pollution haven effect, environmental tax harmonization and competition.

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1 Introduction

World trade expansion and globalization have raised the issue of the relationship between trade and the environment. Most economists believe that expanded trade is generally beneficial, promoting increased efficiency (output) and greater welfare (consumption) among trading countries. But what if expanded trade causes environmental damage? Several influential studies have asked whether international trade is good for the environment (Copeland and Taylor 1994, 1995; Antweiler et al. 2001; Frankel and Rose 2005; Managi et al. 2009). There, however, is no consensus on the impact of trade liberalization on the environment (global pollution emissions).[1] Neither the theoretical nor the empirical literature provides a clean-cut explanation of the trade-environment link and the debate is still inconclusive. Interestingly, in the contrast to the traditional wisdom, some empirical studies have shown that trade may not have a detrimental effect on the global environment (Frankel and Rose 2005) or even have a positive effect for OECD developed countries (Managi et al. 2009).

Substantial evidence has documented that, on the one hand, manufacturing firms make significant contributions to both values of exports and air emissions and, on the other hand, environmental regulations also significantly influence firms' production and market competition (e.g., the entry and exit of firms and market size), see Helland (1998), Becker and Henderson (2000), and Snyder et al. (2003), to name but a few. These observations potentially point to the importance of firm heterogeneity in the link between trade and the environment. In reality, firms are heterogeneous and have different pollution behaviors. Recently, firms' distinctive behaviors in response to trade and environmental regulations have taken center stage in the debate. By focusing on different data, Shadbegian and Gray (2003), Cui et al. (2012), Forslid et al. (2014), and Cao et al. (2016) empirically show that more productive firms exhibit lower emission intensities.[2] Holladay (2016) finds that exporters generate less emissions than non-exporters while the most pollution-intensive firms exit the market under trade liberalization. The relationship between firms' productivities and governments' environmental regulations, however, does not seem to be clear: productivity may either negatively (see Greenstone et al. 2012) or positively (see Berman and Bui 2001) respond to environmental regulations.

This paper, based on these observations, aims to provide the implications of firm heterogeneity for global pollution and trade liberalization. Our model has two novel features. First, we follow Melitz and Ottaviano's (2008) specification to endogenize firms' markups. Because endogenous markups feature a tougher competitive environment and induce *the pro-competitive effect*, *the selection effect* of trade

[1] In the literature on trade and the environment, there are three channels of international trade affecting global pollution emissions: the scale, technique and composition effects (see Antweiler et al. 2001 and Cole and Elliott 2003). The scale effect indicates that openness to trade increases output that results in an increase in global pollution emissions. The technique effect, however, indicates that trade increases income, which calls for cleaner production technology and hence decreases global pollution emissions. The composition effect indicates that trade alters the composition of national output in a way that depends on a nation's comparative advantage.

[2] Shadbegian and Gray (2003) focused on the US paper mills industry data, Cui et al. (2012) focused on the facility-level data of the US manufacturing industry, Forslid et al. (2014) focused on Swedish firm-level data, and Cao et al. (2016) focused on Chinese firm-level data.

liberalization forcing the inefficient firms to exit is amplified, which gives rise to a more favorable effect on the global environment. Second, the environmental regulation stringency considers not only environmental taxation but also its enforcement. It is increasingly recognized that the efficacy of environmental regulations in controlling pollution emissions has been dampened by a lack of appropriate monitoring and enforcement. A careful design of environmental taxes, as stressed by Harford (1978) and Cohen (1999), should include an enforcement mechanism to deter non-compliance and tax evasion; firms may intentionally not comply with the environmental tax by underreporting the amount of emissions (Foulon et al. 2002).[3] In the developing countries, non-compliance with environmental regulations (or illegal emissions) is an important reason for the existence of the pollution haven effect, but recent trade and environmental policy debates still take it as given.

With these model features, we show that firms with distinctive productivities respond to a uniform environmental regulation differently in terms of their output, emissions, and non-compliance with environmental regulations, which in turn changes the competitive structure in both domestic and international markets. For simplicity, the environmental regulation is measured by a simple proportional tax on emissions without taking into consideration an ambient tax that is often used to stratify clean and dirty firms, as in Berliant et al. (2014).[4] Accordingly, we disentangle the interaction effects of emission taxes and trade liberalization on a firm's entry-exit, market size, and global output and pollution.

In autarky, we show that a more stringent environmental regulation shifts production away from inefficient firms to efficient firms with lower costs, resulting in a rise in the average productivity of the market. This result supports the Porter hypothesis in the sense that a stricter environmental regulation forces firms to more aggressively enhance their competitiveness for offsetting the additional cost of environmental regulations, which rules out less competitive firms (see Porter and Van der Linde 1995). While *a stricter environmental regulation favors efficient firms*, some of the efficient firms may produce more emissions in order to expand their output as the production is more emission intensive (or natural resource dependent). In particular, non-compliance with the environmental regulation provides a black market for these firms to escape from the regulation and maintain their competitiveness. In addition, our results show that a negative relationship exists between environmental regulation stringency and the number of firms that is consistent with the empirical finding (see Deily and Gray 1991; Helland 1998; Snyder et al. 2003; Blair and Hite 2005).

In a symmetric two-country economy (with an identical environmental regulation), we investigate whether trade liberalization increases global pollution emissions. The neoclassical trade model predicts

[3] Based on a well-known early study conducted by the White House Council on Environmental Quality, Russell (1990) estimated the rates of compliance with air pollution limits by industrial sources. He found that the percentage of sources in violation was 65, the percentage of time the sources were in violation was 11, and the excess emissions as a percentage of standards was 10. The US General Accounting Office (1990) found that only 200 of 921 polluters thought to be in compliance actually were. In the UK, the compliance rates with key water quality standards can be as low as 50%, and the true compliance rates are more likely to be even lower.

[4] Berliant et al. (2014) showed that an environmental tax with a fixed cost tax component can, by itself, lead to stratification between clean and dirty firms without heterogeneous preferences or increasing returns.

that trade liberalization increases the world-wide output and *the scale effect* gives rise to an unfavorable impact on global pollution emissions (see, for example, Copeland and Taylor 1994). Recent evidence, however, shows that trade may decrease global pollution emissions (see Antweiler et al. 2001; Frankel and Rose 2005). In the model, we show that trade liberalization brings non-exporters keener competition from foreign competitors. This, on the one hand, forces inefficient firms that have higher pollution densities to exit the market, and on the other hand, leads the surviving non-exporters to reduce their output and hence emissions. The *selection effect* of trade liberalization is reinforced, due to the pro-competitive effect of endogenous markups. In our model, as the selection effect dominates the scale effect, trade liberalization decreases, rather than increases, global pollution emissions. Our results indicate that trade liberalization can break the output-environment trade-off, not only increasing the world-wide output but also decreasing global pollution emissions. This reconciles the disparity between the theoretical prediction and the recent empirical findings.

Besides, firms respond to trade liberalization quite differently; the different responses appear not only between non-exporters and exporters but also among exporters. Low trade costs induce some non-exporters to export and less efficient exporters tend to underreport more emissions in order to intensively use emissions for supporting the foreign demand. Under the environmental regulation with non-compliance, *trade liberalization favors less efficient exporters* in the sense that not only does the mass of less efficient exporters expand but the output of each also increases. By contrast, more efficient exporters reduce their output and decrease emissions, including illegal emissions. These efficient exporters exhibit an extensive margin response in the sense that the mass of exporters increases but the output of each exporter decreases.

In an asymmetric two-country economy (with different environmentally regulatory stringency), we confirm the pollution haven effect, showing that trade-induced emissions shift away from one country to the other with loose environmental regulations.[5] Global pollution emissions, however, unambiguously decrease if any one country unilaterally increases the stringency of environmental regulations. Although the pollution haven effect has proved difficult to demonstrate empirically, a few recent studies, as noted in Levinson and Taylor (2008), have shown statistically significant pollution haven effects. As for the country with a stricter environmental regulation (a higher emission tax), higher environmental costs decrease this country's international competitiveness, resulting in a decrease in the numbers of entrants, surviving firms and exporters. The impact is more pronounced if trade costs are substantially low (high openness to trade). Thus, a higher emission tax strongly discourages entry, leading to a less competitive domestic market. Because inefficient firms survive, the average productivity in this country decreases as a response. A higher emission tax thus decreases not only the total output but also the average

[5] The pollution haven effect can be coined as "carbon leakages" in the literature on climate change policy. Since the Kyoto Protocol in December 1997, a number of industrialised countries have committed themselves to unilaterally reducing their emissions of greenhouse gases. Unilateral carbon abatement efforts, however, will increase production costs and undermine international competitiveness that in turn shifts international production and additional emissions to countries that are not subject to an emission constraint. See Burniaux and Martins (2012).

productivity for this country. Of particular interest is that a more stringent environmental regulation *increases the average productivity of firms* in a closed economy but it *decreases the average productivity of firms* in a highly open economy. This ambiguity explains why the literature lacks empirical evidence for the Porter hypothesis (see Jaffe et al. 1995; Greenstone et al. 2012).

In the welfare analysis, we examine the optimal environmental taxation in both cooperative (tax harmonization) and non-cooperative (tax competition) cases. At the national level, the standard socially optimal policy is to internalize environmental externalities. However, at the international level, the burden of environmental externalities must be associated with the pressure of international competition. We show that the optimal environmental tax and the openness to trade exhibit a U-shaped relationship regardless of whether under tax harmonization or tax competition. The U-shaped relationship implies that an extremely low trade cost may end up with more global pollution emissions which call for a higher environmental tax. Of importance, trade liberalization unambiguously decreases global pollution emissions under tax harmonization whereas it may increase global pollution emissions under tax competition. It is always better for the whole world to fight pollution by cooperatively designing a harmonized environmental policy. International cooperation in environmental policy is important in the face of great trade expansion. These results offer a caution to non-cooperative practices in the global environmental regulations. In practice, the authority that formulates and enforces environmental policies usually exists only at the national level, whereas most international trade agreements do not include any provisions for environmental protection.

There is a thin literature that incorporates the pollution generating process of Copeland and Taylor (1994) in a heterogeneous-firm framework *à la* Melitz (2003). Li (2008), Yokoo (2009), and Bajona et al. (2012) show that, under stricter environmental regulations, firms with heterogeneous productivity all react in the same way by reducing their outputs and emissions. Moreover, trade liberalization unambiguously increases global pollution emissions since the scale effect always dominates the selection effect. In the sharp contrast to their results, when we take into account both endogenous markups and non-compliance with the environmental regulation, efficient firms not only respond to the emission tax differently from those less efficient firms, but they may also behave differently within the efficient group. Because the pro-competitive effect, stemming from endogenous markups, reinforces the selection effect, giving rise to a more favorable effect on global environment, trade liberalization can decrease, rather than increase, global pollution emissions.

Recent studies have shed light on the technique effect of international trade. By extending Melitz's (2003) model, Kreickemeier and Richter (2014) 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. To support the empirically negative relationship between trade and global pollution, Baldwin and Ravetti (2014), Forslid et al. (2014), and Kreickemeier and Richter (2014) consistently provide a new link between trade and investments in abatement technology, showing that emission intensity is negatively related to firms' productivity and exports. Because a larger production scale supports more abatement investment, openness to trade can thus lower global pollution emissions by promoting investment in cleaner technology.[6] Differing from their channels, our analysis sheds light on the pro-competitive effect and shows that trade liberalization can decrease global pollution emissions without an abatement technique effect being taken into consideration.

2 Autarky

For the sake of clarity, in this section we first construct an autarky model to investigate the behaviors of firms with different productivities on production and emission strategy (the amount of emissions and the extent of environmental compliance) and examine the entry-exit of firms and the competition of market under the government's environmental regulation. In the next section, we will extend the model to a two-country setting with trade, and explore the interacted effect between trade liberalization and environmental regulation.

2.1 Preferences and Demand

There is one unit mass of identical consumers. They derive utility from consuming a homogeneous good q_0 (chosen as the numéraire) and a continuum of differentiated products q_i (with $i \in \Omega$) but incur disutility from the total pollution emissions Z generated by the production process of firms. Following Yokoo (2009), Kreickemeier and Richter (2014), and Bajona et al. (2012), we consider a separable utility function of the consumption and pollution emissions. The utility of consumption takes a quasi-linear form as in Melitz and Ottaviano (2008):

$$U = q_0 + \alpha \int\limits_{i\in\Omega} q_i di - \frac{\beta}{2} \int\limits_{i\in\Omega} (q_i)^2 \, di - \frac{\gamma}{2} \left(\int\limits_{i\in\Omega} q_i di \right)^2 - h(Z), \;\; \alpha, \beta, \gamma > 0. \tag{1}$$

A higher α reflects a stronger preference for the differentiated varieties compared to the numéraire, a higher β reflects a stronger bias towards product differentiation (a preference for variety), and a higher γ reflects a higher degree of substitutability between varieties. Pollution interferes with consumers' utility as a negative externality $(-h(Z))$, where $h(Z)$ is an increasing $(\frac{\partial h}{\partial Z} > 0)$ and convex function $(\frac{\partial^2 h}{\partial Z^2} > 0)$. As an externality, consumers take Z as given, while in equilibrium it is endogenously determined by firms' emission use.

Suppose that each consumer supplies one unit of labor inelastically. Thus, the budget constraint facing an individual consumer is given by:

$$\int\limits_{i\in\Omega} (p_i q_i) di + q_0 = \bar{q}_0 + w + TR, \tag{2}$$

[6] Although Cao et al. (2016) also adopt the utility function of Melitz and Ottaviano (2008), their analysis is restrained in a closed economy that abstracts from the effect of trade.

where $\bar{q}_0$ is the initial endowment, w is the wage rate and TR is the lump-sum transfer from the government. The endowment $\bar{q}_0$ is large enough to ensure positive demand for the numéraire good ($q_0 > 0$). Hence, the inverse demand for each variety i can be derived as:

$$p_i = \alpha - \beta q_i - \gamma Q, \tag{3}$$

where p_i is the (relative) price of variety i (to the numéraire good) and $Q \equiv \int_{i \in \Omega} q_i di$ denotes the aggregate market demand over all varieties. In contrast to the constant elasticity of substitution (CES) demand system, the linear demand function (3) implies that the price elasticity of demand (and hence the firm's price markup) is not uniquely determined by constant parameters, but instead affected by endogenous average market prices and the number of competing varieties. This, as stressed by Melitz and Ottaviano (2008), features a tougher competitive environment and entails the so-called pro-competitive effect that is crucial to our analysis.

2.2 Production and Emissions

The supply of differentiated goods is characterized by monopolistic competition under which firms are heterogeneous in terms of their productivity, as denoted by ϕ. Firms produce output q under an environmental regulation in the sense that firms are levied an emission tax t based on their reported emissions r. Since firms do not perfectly comply with the environmental regulation, the reported amount of emissions is not necessarily consistent with the true amount that a firm emitted, z. To evade emission taxes (i.e., environmental regulatory non-compliance), firms may underreport the true amount of emissions, i.e., $r < z$. Once a reporting violation is detected through an audit, the firm will be penalized at F ($> t$) for each unit of the underreported emissions (or illegal emissions), $e = z - r$. Since monitoring for compliance by the authorities is imperfect, the probability π that the authority will be able to detect a reporting violation of firms is less than one, i.e., $0 < \pi < 1$. To satisfy the decreasing marginal benefit of underreported emissions, the detection probability is assumed to be increasing in the ratio of illegal emissions, i.e., $\pi = \pi_0(\frac{z-r}{z})$ with an exogenous detection parameter π_0. For simplicity of expression, we assume $\pi_0 = 1$ in the following analysis.[7]

In line with Copeland and Taylor (1994), the production function of a firm with productivity ϕ is given by:

$$q(\phi) = \phi z(\phi)^{\lambda} l(\phi)^{1-\lambda}, \; 0 < \lambda < 1 \tag{4}$$

where $z(\phi)$ is the emissions (polluting input) with λ being the emission share and $l(\phi)$ is the labor (non-polluting input) with $(1 - \lambda)$ being the labor share. Emissions as an input reflects the idea that the services provided by the natural environment (including its function as a weak sink) enable the firm to increase its level of output for any given input of other factors. Copeland and Taylor (1994) provide

[7] That emissions tend to be underreported may be a result of corruptible bureaucrats (see Fredriksson and Svensson 2003). Under such a scenario, our results hold true as the expected cost of underreported emissions is simply thought of as the bribery payment.

a clear microfoundation for such a specification of the production function, indicating that a firm has two non-exclusive options to reduce its emissions by either reducing the production level q or specific emissions z. Given the emission taxation (t) and its enforcement (the penalty F and the detection probability π), the firm's (expected) cost C is:

$$C = wl + tr + \pi F(z - r), \tag{5}$$

where $\pi = \frac{z-r}{z}$. With the production technology of (4), the minimization of the expected cost (5) yields the optimal amount of labor, actual and reported emissions:

$$l = [\frac{\lambda w}{(1-\lambda)\chi(t,F)}]^{-\lambda}\frac{q}{\phi}, \tag{6}$$

$$z = [\frac{\lambda w}{(1-\lambda)\chi(t,F)}]^{1-\lambda}\frac{q}{\phi}, \tag{7}$$

$$r = (1 - \frac{t}{2F})z = (1 - \frac{t}{2F})[\frac{\lambda w}{(1-\lambda)\chi(t,F)}]^{1-\lambda}\frac{q}{\phi}, \tag{8}$$

where $\chi(t,F) \equiv t\left(1 - \frac{t}{4F}\right)$ is the effective price of emissions which increases with the emission tax t and penalty F.[8] Substituting (6)-(8) into (5), the firm's cost function (indexed by ϕ) is:

$$C_\phi(q) = \eta[\chi(t,F)]^\lambda w^{1-\lambda}\frac{q}{\phi} = \Psi(t,F)w^{1-\lambda}\frac{q}{\phi}, \tag{9}$$

where $\Psi(t,F) \equiv \eta[\chi(t,F)]^\lambda$ with $\eta \equiv \lambda^{-\lambda}(1-\lambda)^{-(1-\lambda)}$.

Under perfect competition, the numéraire good is produced by labor only under constant returns to scale at unit cost. With a fixed labor supply, the perfectly competitive labor market implies a unit wage rate, $w = 1$. Let $c \equiv \frac{1}{\phi}$, and thus we refer to firms with a productivity index ϕ as firms with a cost index c. By following Melitz (2003) and Melitz and Ottaviano (2008), prior to entry into the market, *ex ante* firms incur a fixed cost f (in terms of labor) to set up plants and production lines and to engage in R&D underpinning the introduction of a new variety. The start-up cost f is irreversible and is sunk after entry. R&D yields uncertain outcomes for the cost c which is recognized after paying the irreversible set-up f for entry. The value of c is modeled as a draw from a common (and known) distribution $G(c)$ with support on $[0, c_m]$. Unlike the standard models of heterogeneous firms and trade, firms' costs are not purely given by their randomly drawn productivity, but also by their deliberate choices regarding the use of polluting input z and the compliance with the environmental regulation r. It follows from (9) that the marginal cost $c \cdot \Psi(t,F)$ is not only governed by the drawn c but is also affected by the environmental regulation (t,F).

Given that f is sunk after entry, some firms that can cover their marginal costs survive and produce while other firms exit and do not produce.[9] A surviving firm with cost c, subject to the residual demand

[8] From (7)-(8), we can obtain the optimality condition for the two inputs of labor and emissions $\frac{w}{\chi(t,F)} = \frac{\beta\lambda\phi z(\phi)^{\lambda-1}l(\phi)^{1-\lambda}}{\beta(1-\lambda)\phi z(\phi)^{\lambda}l(\phi)^{-\lambda}}$, indicating that the marginal rate of technical substitution (MRTS) is equal to the ratio of (after-tax) factor-input prices.

[9] By following Melitz and Ottaviano (2008), we do not model any production fixed costs given that the existence of the fixed costs degrades the tractability of the model without adding any new insights. In this model with bounded marginal utility, firms with relatively high costs will not survive even without such fixed costs.

function (3), maximizes its profits:

$$\Pi(c) = [p(c) - c\Psi(t, F)]\, q(c).$$

This profit maximization yields the following optimal output:

$$q(c) = \frac{\alpha - \gamma Q - c\Psi(t, F)}{2\beta}. \tag{10}$$

Define c_D as a critical level that makes a firm indifferent between remaining in the market or not. This critical firm earns zero profit as its price is driven down to its marginal cost, $p(c_D) - c_D\Psi(t, F) = 0$, and its demand level $q(c_D)$ is driven to 0. We assume $c \in [0, c_m]$ so that firms with lower cost $0 \leq c \leq c_D$ earn positive gross profits and remain in the market, whereas others with higher cost $c_D < c \leq c_m$ exit the market. Because the zero-profit condition implies either $p(c_D) - c_D\Psi(t, F) = 0$ or $q(c_D) = 0$, (10) enables us to derive the aggregate output:

$$Q = \frac{\alpha - c_D\Psi(t, F)}{\gamma}. \tag{11}$$

With (11), we can use (3), (10), (7) and (6) to obtain:

$$p^*(c) = \frac{\Psi}{2}(c_D + c), \tag{12}$$

$$q^*(c) = \frac{\Psi}{2\beta}(c_D - c), \tag{13}$$

$$z^*(c) = \frac{c\Psi}{2\beta}\left[\frac{\lambda}{(1-\lambda)\chi}\right]^{1-\lambda}(c_D - c), \tag{14}$$

$$l^*(c) = \frac{c\Psi}{2\beta}\left[\frac{\lambda}{(1-\lambda)\chi}\right]^{-\lambda}(c_D - c), \tag{15}$$

$$\mu^*(c) \equiv \frac{p^*(c)}{c\Psi} = \frac{(c_D + c)}{2c}, \tag{16}$$

where these variables are all affected by the emission tax, reflected in Ψ and χ (we hereafter refer to $\Psi(t, F)$ and $\chi(t, F)$ as Ψ and χ to simplify our expressions).

It is straightforward to see that more efficient firms with lower c set lower prices p^* and produce more output q^* while their markups μ^* are higher. With higher output, more efficient firms tend to have lower *pollution density* $\frac{z^*(c)}{q^*(c)} = c\left[\frac{\lambda}{(1-\lambda)\chi}\right]^{1-\lambda}$, which supports empirical findings (Shadbegian and Gray 2003; Forslid et al. 2014). Although efficient firms with lower c always have lower emission density, they may produce either more or less emissions $z^*(c)$ (in absolute level terms), depending on the condition of $c \gtrless \frac{c_D}{2}$. On the one hand, efficient firms generate more output and this scale effect leads efficient firms to generate more emissions. On the other hand, efficient firms have lower pollution density which, given a certain level of output, enables them to produce goods with less emissions. In the model with endogenous markups $\mu^*(c)$, the output gap between efficient and inefficient firms becomes smaller. This weakens the former output effect, leading to an ambiguous effect on the emission choice for firms with heterogeneous productivities. Once the output effect is dominated, more efficient firms will generate less emissions not only in absolute terms (the amount of emissions $z^*(c)$) but also in relative (the pollution density $\frac{z^*(c)}{q^*(c)}$) terms. This result is different from that obtained in models with CES demand and fixed markups, such as Yokoo (2009) and Bajona et al. (2012) who refer to a positive relationship between emissions and productivity.

Finally, from (8) we have the underreported emissions (illegal emissions) as follows:

$$e^*(c) = z^*(c) - r^*(c) = \frac{t\Psi}{4F\beta}\left[\frac{\lambda}{(1-\lambda)\chi}\right]^{1-\lambda}(c_D - c)c. \tag{17}$$

Similar to emissions $z^*(c)$, more efficient firms with a lower c do not necessarily have more or less illegal emissions $e^*(c)$, depending on the same condition $c \gtrless \frac{c_D}{2}$. This implies that to produce more output, efficient firms can emit more pollution by underreporting more emissions. Otherwise, they may decrease the actual and unreported emissions simultaneously.

2.3 Government

The government balances its budget by collecting the emission tax and penalty revenues and rebating these revenues to consumers in a lump-sum manner. The government budget constraint is given by:

$$TR = t \cdot R + \pi \cdot F \cdot (Z - R), \tag{18}$$

where Z and R are the economy-wide total (actual) and reported emissions, respectively. In our model, the non-distortionary lump-sum transfers TR, on the one hand, lead the government to meet its budget constraint and, on the other hand, isolate the effects of the emission tax from those of distortionary government spending.

2.4 Free Entry Equilibrium

Firms learn their productivity levels $c \equiv \frac{1}{\phi}$ after making the irreversible set-up f for entry. Prior to entry, the zero expected profit yields the free entry condition:

$$\int_0^{c_D} \Pi(c)dG(c) = f, \tag{19}$$

which pins down the cut-off c_D in equilibrium. In line with Melitz and Ottaviano (2008), firms' productivities $1/c$ follow a Pareto distribution with lower productivity bound $1/c_m$ and shape $\kappa \geq 1$, i.e.:

$$G(c) \equiv \left(\frac{c}{c_m}\right)^{\kappa}, \; c \in [0, c_m]$$

where we assume $c_m > \frac{\sqrt{2(1+\kappa)(2+\kappa)\beta f}}{\Psi}$ to ensure that $c_D < c_m$. The shape parameter κ indexes the dispersion of cost draws. When $\kappa = 1$, the distribution reduces to a uniform one. As κ increases, the relative number of high-cost firms increases, and the cost distribution is more concentrated at these higher cost levels. If κ goes to infinity, the distribution degenerates at c_m. Any truncation of the cost distribution from above will retain the same distribution function and shape parameter κ.

We solve the free-entry condition (19) to determine the cost cut-off:

$$c_D = \left[\frac{2\beta f c_m^{\kappa}}{\Psi^2}\left(2+3\kappa+\kappa^2\right)\right]^{\frac{1}{2+\kappa}}. \tag{20}$$

Because $c_D < c_m$, entrants do not necessarily survive; inefficient firms leave the market. For those surviving firms, the Pareto truncated cost distribution is $G_D(c) \equiv \left(\frac{c}{c_D}\right)^{\kappa}$, with $c \in [0, c_D]$. In particular, the emission taxation (captured by Ψ or χ) influences not only firms' price setting and markups but also decisions on entry and exit. It follows from (12), (16), and (20) that the emission tax Ψ creates an additional production cost for firms, which raises the market price $p^*(c)$ but lowers firms' markups $\mu^*(c)$, forcing some firms with relatively high costs to exit the market (a decrease in the cut-off c_D).

The market-clearing condition for differentiated goods is given by:

$$Q = M\int_0^{c_D} q(c)dG(c), \tag{21}$$

where M is the number of entrants. With the labor market-clearing condition, substituting (13) and (20) into (21) yields the equilibrium number of entrants:

$$M^* = \frac{2\beta(1+\kappa)}{\gamma(c_D/c_m)^{\kappa}}\left(\frac{\alpha}{\Psi c_D}-1\right).$$

Accordingly, the number of firms surviving in the market can be derived as:

$$N^* = M^*\int_0^{c_D} dG(c) = \frac{2\beta\left(1+\kappa\right)}{\gamma}\left(\frac{\alpha}{\Psi c_D}-1\right), \tag{22}$$

where we assume $\alpha > \Psi c_D = \left[\beta f c_m^{\kappa}\left(4+6\kappa+2\kappa^2\right)\Psi^{\kappa}\right]^{\frac{1}{2+\kappa}}$ to guarantee $N^* > 0$. Thus, in the whole economy the aggregate emissions Z^* and illegal emissions E^* respectively are:

$$Z^* = M^*\int_0^{c_D} z^*(c)dG(c) = \frac{\lambda\kappa c_D(\alpha-\Psi c_D)\eta^{\frac{1}{\lambda}}\Psi^{\frac{\lambda-1}{\lambda}}}{(2+\kappa)\gamma}, \tag{23}$$

$$E^* = M^*\int_0^{c_D} z^*(c)dG(c) - M^*\int_0^{c_D} r^*(c)dG(c) = \frac{t\lambda\kappa c_D(\alpha-\Psi c_D)\eta^{\frac{1}{\lambda}}\Psi^{\frac{\lambda-1}{\lambda}}}{2F(2+\kappa)\gamma}. \tag{24}$$

2.5 Effects of Environmental Regulations

Based on the results above, we arrive at a proposition as follows:

Proposition 1 *In response to a more stringent environmental regulation (increasing the emission tax t or the penalty F),*

(i) *the cut-off c_D decreases, resulting in an increase in the average productivity of firms (a lower $\bar{c}$),*

(ii) *the product price $p^*(c)$ increases while the markup $\mu^*(c)$ decreases for all $c < c_D$,*

(iii) *the number of surviving firms N^* decreases,*

(iv) *the economy-wide output Q^* and total emissions Z^* decrease, and*

(v) *the total amount of illegal emissions E^* unambiguously decreases with the penalty for violation F, whereas it may increase with the emission tax t.*

Proof. All proofs are relegated to the Appendix. ■

A more stringent environmental regulation (t or F) raises the marginal cost of production, shifting production away from less efficient firms to more efficient firms. Because less efficient firms exit the market, the emission tax generates average productivity gains (a lower $\bar{c}$) for the economy. This result, to some extent, supports the Porter hypothesis in the sense that a stricter environmental regulation forces firms to more aggressively enhance their competitiveness to offset the additional cost of environmental regulations, which rules out less competitive firms. Therefore, the environmental regulation leads to a greater exit of firms and, as a result, the number of surviving firms N^* falls. The negative relationship between environmental regulation stringency and the number of firms is also consistent with the empirical finding (see Deily and Gray 1991; Helland 1998; Snyder et al. 2003; Blair and Hite 2005).

A stricter environmental regulation raises the input price of emissions, and thus increases the product price p^*. As a result, the economy-wide output Q^* and total emissions Z^* decrease. In addition, because the average productivity in the market rises (a lower $\bar{c}$), an environmental regulation generates a tougher competitive environment and the pro-competitive effect lowers the markup μ^* of products. Of interest, raising the penalty for violation F discourages firms from emitting pollution illegally but raising the emission tax t may encourage firms to increase their illegal emissions E^*. While a higher emission tax decreases firms' demand for emissions and hence the amount of concealed emissions, it also creates an incentive for firms to evade the emission tax. If the latter effect dominates, the total amount of illegal emissions increases, rather than decreases, with the emission tax. The UK landfill regulation provides a typical example for the distinction between the environmental taxation and its enforcement. The UK government still cannot guarantee compliance with the quantity targets set by the Landfill Directive even though it has raised the landfill tax to very high levels. Failure to meet these mandatory EU targets thereby subjects the UK to substantial penalties for non-compliance (see Fullerton 2010).

Of particular note here is the trade-off relationship between output and environmental quality (or pollution). In terms of the economy-wide perspective, there indeed exists a trade-off between total output Q^* and environmental quality Z^*. Although a more stringent environmental regulation decreases total emissions, it also hurts the economy-wide output. However, in terms of the firm-wide perspective, such a trade-off may break down. In our model with endogenous markups, the responses of price setting are not proportional to those of the production cost. Moreover, the non-compliance with the regulation provides another way for firms to use the polluting input (emissions) to compete with their rivals. Thus, firms with different costs will respond to the environmental regulation very differently such that the positive output-emission relationship, as we will see below, may not hold from a firm-wide perspective.

To shed light on the implications for firm heterogeneity, two different cases are considered. One refers to the case where firms have relatively high polluting-input intensity ($\frac{2+\kappa}{2(1+\kappa)} < \lambda < 1$), implying that the production is more natural resource dependent. The other refers to the case where firms have relatively low polluting-input intensity ($0 < \lambda < \frac{2+\kappa}{2(1+\kappa)}$), implying that the production is less natural resource dependent. Let $c_z \equiv \frac{2+\kappa-2\lambda(1+\kappa)}{(1-2\lambda)(2+\kappa)}c_D$, $c_q \equiv \frac{1+\kappa}{2+\kappa}c_D$, and $c_e \equiv \frac{4\lambda(1+\kappa)(2F-t)+(2+\kappa)t}{(2+\kappa)(8\lambda F+t-4\lambda t)}c_D$. Based on Figures 1 and 2, we thus have following two lemmas:

Lemma 1 *In response to a higher emission tax t,*

(i) *firms with the lowest costs ($0 < c < c_z$),*

- **a.** *produce more output $q^*(c)$ and more emissions $z^*(c)$, and underreport more emissions $e^*(c)$ under the case where $\frac{2+\kappa}{2(1+\kappa)} < \lambda < 1$;*
- **b.** *produce more output $q^*(c)$ and less emissions $z^*(c)$, and underreport more emissions $e^*(c)$ under the case where $0 < \lambda < \frac{2+\kappa}{2(1+\kappa)}$;*

(ii) *firms with relatively low costs ($c_z < c < c_q$) produce more output $q^*(c)$ and less emissions $z^*(c)$, and underreport more emissions $e^*(c)$;*

(iii) *firms with relatively high costs ($c_q < c < c_e$) produce less output $q^*(c)$ and less emissions $z^*(c)$, and underreport more emissions $e^*(c)$;*

(iv) *firms with the highest costs ($c_e < c < c_D$) produce less output $q^*(c)$ and less emissions $z^*(c)$, and underreport less emissions $e^*(c)$.*

Lemma 2 *In response to a higher penalty for illegal emissions F, the amount of unreported emissions $e^*(c)$ is unambiguously reduced for all firms, while*

(i) *firms with the lowest costs ($0 < c < c_z$) produce more output $q^*(c)$ and more emissions $z^*(c)$;*

(ii) *firms with relatively low costs ($c_z < c < c_q$) produce more output $q^*(c)$ but less emissions $z^*(c)$;*

(iii) *firms with the relatively high and the highest costs ($c_q < c < c_D$) produce less output $q^*(c)$ and less emissions.*

In the model with fixed markups (due to a CES utility), a higher emission tax unambiguously leads all firms to reduce their output and emissions (see Yokoo 2009; Bajona et al. 2012). Lemma 1, however, shows that endogenous markups, together with firms' non-compliance with regulation, leads firms with different costs to respond to the environmental regulation differently (in terms of the output, actual and underreported emissions). As noted in the Introduction, many empirical studies have found ample evidence, showing that the existence of heterogeneous productivity among firms governs their environmental performance.

As shown in Proposition 1, a higher emission tax t increases the input price of emissions, which induces firms to set higher product prices $p(c)$. However, a higher input price has *less* strong impact on raising the production cost of efficient firms than that of inefficient firms because efficient firms have higher productivity in the sense that they require fewer inputs to produce each unit of output. Therefore, efficient firms with lower costs ($0 < c < c_q$) raise prices less than inefficient firms with higher costs ($c_q < c < c_D$).[10] In other words, lower production costs enable efficient firms to expand their output levels by setting lower prices to maintain their competitiveness under a stricter environmental regulation. Thus, the equilibrium output $q^*(c)$ of efficient firms with $0 < c < c_q$ increases in response to a higher emission tax. By contrast, a higher emission tax t has a stronger impact on the cost of inefficient firms with relatively high and the highest costs ($c_q < c < c_D$) because their production rely on more emission inputs (i.e., higher pollution densities). Due to this disadvantage, a higher emission tax forces these inefficient firms to cut their output and raise their prices more markedly. An important finding is that the trade-off between economic output and environmental quality is broken down for these efficient firms.

For those firms with the lowest costs ($0 < c < c_z$), the amount of emissions $z^*(c)$ increases in order to support higher output levels if the production is more natural resource dependent (i.e., more emission intensive, $\frac{2+\kappa}{2(1+\kappa)} < \lambda < 1$). By contrast, the amount of emissions decreases with a higher emission tax because the polluting input is replaced by labor as the production is less natural resource dependent (i.e., less emission intensive, $0 < \lambda < \frac{2+\kappa}{2(1+\kappa)}$). Firms with relatively low costs ($c_z < c < c_q$) have similar responses to the emission tax. Interesting, these efficient firms with $0 < c < c_q$, on the one hand, expand output to maintain their competitiveness and, on the other hand, increase illegal emissions to partially offset the additional cost caused by a stricter environmental regulation (recalling that a higher emission tax provides a higher return to tax evasion). By contrast, for firms with relatively high and the highest costs ($c_q < c < c_D$), they are more adversely affected by a higher emission tax, leading these less efficient firms to decrease their output $q^*(c)$ and emissions $z^*(c)$. For firms with the highest costs ($c_e < c < c_D$), because the use of emissions is reduced substantially, they decrease not only the overall emissions but also illegal emissions $e^*(c)$. It seems that a more stringent environmental regulation favors those firms with lower costs, leading them to produce more output via increasing emissions (including illegal emissions).

Lemma 2 shows that although a stronger enforcement of the environmental regulation (a higher penalty of violations F) unambiguously decreases illegal emissions for all firms, it leads some firms to increase, rather than decrease, their emissions. Similar to the emission tax t, the penalty F is also in favor of efficient firms. To maintain their competitiveness, a higher F allows firms with the lowest costs ($0 < c < c_z$) to expand their output $q^*(c)$ by using more polluting input and generating more emissions $z^*(c)$, because the pro-competitive effect leads the environmental regulation's enforcement

[10] With endogenous markups, a higher emission tax decreases the markup for efficient firms more markedly, and hence increases their prices less.

to have the weakest impact on them. As for firms with relatively low costs ($c_z < c < c_q$), when faced with a higher penalty, they will tend to substitute more labor for emissions, which in turn will increase their output levels. As for firms with relatively high and the highest costs ($c_q < c < c_D$), they are forced to decrease their output and emissions because a higher penalty brings them more pronounced environmental costs.

We summarize the main results in the following proposition:

Proposition 2 *A more stringent environmental regulation favors efficient firms with lower production costs.*

(i) *in the presence of a higher emission tax t,*

- **a.** *firms with the lowest and relatively low costs ($0 < c < c_q$) can produce more goods $q^*(c)$ but generate less emissions $z^*(c)$ (the pro-competitive effect), provided that their production is less natural resource dependent ($0 < \lambda < \frac{2+\kappa}{2(1+\kappa)}$). The trade-off between outputs and the environment does not exist for these firms.*
- **b.** *firms with the lowest costs ($0 < c < c_z$) may produce more emissions $z^*(c)$ to support higher output and maintain competitiveness as their production is more natural resource dependent ($\frac{2+\kappa}{2(1+\kappa)} < \lambda < 1$).*
- **c.** *illegal emissions $e^*(c)$ increase for efficient firms ($0 < c < c_e$) given that the existence of non-compliance with the regulation provides a black market to escape from the regulation and render production efficiency.*

(ii) *in the presence of a higher penalty for illegal emissions F,*

- **a.** *illegal emissions $e^*(c)$ unambiguously decrease for all firms while the amount of emissions $z^*(c)$ increases for the efficient firms ($0 < c < c_z$) only.*
- **b.** *efficient firms with the lowest costs ($0 < c < c_z$) generate more emissions $z^*(c)$ to support their higher output but firms with relatively high and the highest costs ($c_q < c < c_D$) generate less emissions due to a decrease in their output (the scale effect).*

3 Two-Country World

In this section, we extend the model of the previous section to a two-country setting with trade, and investigate the interaction effects of environmental regulations and trade liberalization on the firm's emission strategy (in both the amount of emissions and the extent of environmental non-compliance), the market's competition (within and between countries), and the global pollution (in terms of the pollution haven effect).

Consider two countries, $j = 1, 2$, where each country has one unit mass of consumers. The two countries are assumed to be symmetric both in consumer preferences given by (1) and in production technologies given by (4), while we allow for asymmetry for governments' environmental regulations (t_j, F_j). The homogeneous good is freely traded and both countries share the same wage rate, which is normalized to unity, e.g., $w_1 = w_2 = 1$. The differentiated good, however, is traded with a positive iceberg trade cost $\tau > 1$ incurred by exporters for both countries; τ units of a good should be shipped in order for one unit to arrive at the destination. For the sake of more clarity in exposition, pollution only has the localized effect (i.e., there is no transboundary pollution) in the two-country model. Our positive analysis holds with transboundary pollution given that pollution is an externality for consumers and its external disutility is separated from consumption (see (1)).

While firms can produce in one market and sell in the other by incurring a per-unit iceberg trade cost τ, the markets are segmented in the two countries. In each country, firms decide whether or not to enter the market and whether or not to export varieties to the foreign market. Owing to market segmentation, the exporter with cost c in Country $j = 1, 2$ makes profits from the domestic market $\Pi_{jj}(c)$ and from exporting goods to the foreign market $\Pi_{jk}(c)$ where $k \neq j$, i.e.:

$$\Pi_{jj}(c) = [p_{jj}(c) - c\Psi_j(t_j, F_j)]\, q_{jj}(c),$$
$$\Pi_{jk}(c) = [p_{jk}(c) - \tau c\Psi_j(t_j, F_j)]\, q_{jk}(c),$$

where $p_{jj}(c)$ $(q_{jj}(c))$ and $p_{jk}(c)$ $(q_{jk}(c))$ are the prices (output levels) for the domestic market j and the foreign market k, respectively. As for a non-exporter located in country j, it makes profits from the domestic market $\Pi_{jj}(c)$ only.

3.1 Open Economy Equilibrium

By applying a similar procedure in Section 2, it is easy to derive the profit maximizing output sold to the domestic market j and the foreign market k as follows. For $j = 1, 2$ and $k \neq j$, we have

$$q_{jj}(c) = \frac{\alpha - c\Psi_j - \gamma Q_j}{2\beta} \text{ and } q_{jk}(c) = \frac{\alpha - \tau c\Psi_j - \gamma Q_k}{2\beta}, \tag{25}$$

where Q_j (Q_k) denotes the aggregate demand in Country j (k). Because only firms earning non-negative profits in a (domestic or foreign) market will choose to sell in that market, we then have similar cost cut-off rules for firms selling in the domestic and the foreign market. Define c_{jj} as the upper-bound cost for firms selling in the domestic market j, and c_{jk} as the upper-bound cost for exporters selling from Country j to k. Accordingly, the zero-profit conditions imply $q_{jj}(c_{jj}) = 0$ and $q_{jk}(c_{jk}) = 0$, and from (25) we have:

$$c_{jj} = \frac{\alpha - \gamma Q_j}{\Psi_j(t_j, F_j)} \text{ and } c_{jk} = \frac{\alpha - \gamma Q_k}{\tau\Psi_j(t_j, F_j)}. \tag{26}$$

With the two cut-offs, we can summarize the domestic and exporting outputs, and the corresponding prices, emissions, labor inputs, and markups of an exporter c located in Country $j = 1, 2$:

$$q_{jj}^{*}(c) = \frac{\alpha - \gamma Q_j - c\Psi_j}{2\beta}, \; q_{jk}^{*}(c) = \frac{\alpha - \gamma Q_k - \tau c\Psi_j}{2\beta}, \tag{27}$$

$$p_{jj}^{*}(c) = \frac{c\Psi_j + \alpha - \gamma Q_j}{2}, \; p_{jk}^{*}(c) = \frac{\alpha - \gamma Q_k + \tau c\Psi_j}{2}, \tag{28}$$

$$z_{jj}^{*}(c) = \frac{c(\alpha - \gamma Q_j - c\Psi_j)}{2\beta\left[\frac{\chi_j(1-\lambda)}{\lambda}\right]^{1-\lambda}}, \; z_{jk}^{*}(c) = \frac{c(\alpha - \gamma Q_k - \tau c\Psi_j)}{2\beta\left[\frac{\chi_j(1-\lambda)}{\lambda}\right]^{1-\lambda}}, \tag{29}$$

$$l_{jj}^{*}(c) = \frac{c(\alpha - \gamma Q_j - c\Psi_j)}{2\beta\left[\frac{\lambda}{\chi_j(1-\lambda)}\right]^{\lambda}}, \; l_{jk}^{*}(c) = \frac{c(\alpha - \gamma Q_k - \tau c\Psi_j)}{2\beta\left[\frac{\lambda}{\chi_j(1-\lambda)}\right]^{\lambda}}, \tag{30}$$

$$\mu_{jj}^{*}(c) = \frac{p_{jj}^{*}(c)}{c\Psi_j} = \frac{c\Psi_j + \alpha - \gamma Q_j}{2c\Psi_j}, \; \mu_{jk}^{*}(c) = \frac{p_{jk}^{*}(c)}{\tau c\Psi_j} = \frac{c\Psi_j + \alpha - \gamma Q_j}{2\tau c\Psi_j}. \tag{31}$$

Moreover, illegal emissions are given by:

$$e_{jj}^{*}(c) = \left(\frac{t_j}{2F_j}\right) z_{jj} = \frac{t_j c(\alpha - \gamma Q_j - c\Psi_j)}{4F_j\beta\left[\frac{\chi_j(1-\lambda)}{\lambda}\right]^{1-\lambda}},$$

$$e_{jk}^{*}(c) = \left(\frac{t_j}{2F_j}\right) z_{jk} = \frac{t_j c(\alpha - \gamma Q_k - \tau c\Psi_j)}{4F_j\beta\left[\frac{\chi_j(1-\lambda)}{\lambda}\right]^{1-\lambda}}.$$

In addition to the two cut-off conditions for entering the domestic and foreign markets (26), solving the open economy equilibrium requires a free-entry condition that brings expected profits to zero. Both countries are assumed to share the same cost structure in terms of the entry cost f and cost distribution $G(c)$. Thus, the zero expected profits of firms located in Country j are given by:

$$\int_0^{c_{ii}} \Pi_{jj}(c)dG(c) + \int_0^{c_{jk}} \Pi_{jk}(c)dG(c) - f = 0,$$

which yields

$$Q_j^{*} = \frac{\alpha - \left[\frac{\xi\left(\Psi_j^{\kappa} - \Psi_k^{\kappa}\rho\right)}{1-\rho^2}\right]^{\frac{1}{2+\kappa}}}{\gamma}, \tag{32}$$

where $\rho = \tau^{-\kappa}$ and $\xi = 2\beta f c_m^{\kappa}\left(2 + 3\kappa + \kappa^2\right)$. To ensure a positive output $Q_j^{*} > 0$, we require $\alpha > \left[\frac{\xi\left(\Psi_j^{\kappa} - \Psi_k^{\kappa}\rho\right)}{1-\rho^2}\right]^{\frac{1}{2+\kappa}}$.

The market-clearing condition in Country $j = 1, 2$ is given by:

$$M_j^{*} \int_0^{c_{jj}} q_{jj}^{*}(c)dG(c) + M_k^{*} \int_0^{c_{kj}} q_{kj}^{*}(c)dG(c) = Q_j^{*}.$$

From the market-clearing conditions of both countries, we obtain the number of entrants in Country j:

$$M_j^{*} = \frac{2\beta(1+\kappa)(c_m\Psi_j)^{\kappa}\left[Q_j^{*}(\alpha - Q_k^{*}\gamma)^{1+\kappa} - \rho Q_k^{*}\left(\alpha - Q_j^{*}\gamma\right)^{1+\kappa}\right]}{(1-\rho^2)\left(\alpha - Q_j^{*}\gamma\right)^{1+\kappa}(\alpha - Q_k^{*}\gamma)^{1+\kappa}}. \tag{33}$$

Equation (33) is a function of the market output levels of both countries Q_j^{*} and Q_k^{*} in the open economy. In addition, we can easily obtain the numbers of surviving firms and of exporters located in

Country $j = 1, 2$ as follows:

$$N_j^* = M_j^* \int_0^{c_{jj}} dG(c) = \frac{2\beta (1+\kappa) \left[Q_j^* (\alpha - Q_k^* \gamma)^{1+\kappa} - \rho Q_k^* \left(\alpha - Q_j^* \gamma \right)^{1+\kappa} \right]}{(1-\rho^2) \left(\alpha - Q_j^* \gamma \right) (\alpha - Q_k^* \gamma)^{1+\kappa}}, \tag{34}$$

$$X_j^* = M_j^* \int_0^{c_{jk}} dG(c) = \frac{2\beta (1+\kappa) \left[Q_j^* (\alpha - Q_k^* \gamma)^{1+\kappa} - \rho Q_k^* \left(\alpha - Q_j^* \gamma \right)^{1+\kappa} \right]}{\rho (1-\rho^2) \left(\alpha - Q_j^* \gamma \right)^{1+\kappa} (\alpha - Q_k^* \gamma)}. \tag{35}$$

Accordingly, the total amount of emissions in Country $j = 1, 2$ is

$$\begin{aligned} Z_j^* &= M_j^* \left[\int_0^{c_{jj}} z_{jj}^*(c) dG(c) + \int_0^{c_{jk}} z_{jk}^*(c) dG(c) \right] \\ &= \frac{\kappa \left(\alpha\text{-}Q_j^* \gamma \right) \left[Q_j^* (\alpha\text{-}Q_k^* \gamma)^{1+\kappa} \text{-} \rho Q_k^* \left(\alpha\text{-}Q_j^* \gamma \right)^{1+\kappa} \right] \left[\frac{\rho}{\tau} (\alpha\text{-}Q_k^* \gamma)^{2+\kappa} + \left(\alpha\text{-}Q_j^* \gamma \right)^{2+\kappa} \right]}{(2+\kappa)(1-\rho^2)(\alpha - Q_k^* \gamma)^{1+\kappa} \left[\frac{\chi_j (1-\lambda)}{\lambda} \right]^{1-\lambda} \Psi_j}. \end{aligned}$$

and hence, the total amount of illegal emissions is $E_j^* = \frac{t_j}{2F_j} Z_j^*$. Meanwhile, we also have the export volumes from Country j to Country k:

$$Q_{jk}^* = M_j^* \int_0^{c_{jk}} q_{jk}^*(c) dG(c) = \frac{\rho Q_j^* (\alpha - Q_k^* \gamma)^{1+\kappa} - Q_k^* \left(\alpha - Q_j^* \gamma \right)^{1+\kappa}}{(1-\rho^2) \left(\alpha - Q_j^* \gamma \right)^{1+\kappa}}. \tag{36}$$

3.2 Symmetric Equilibrium with a Unified Environmental Regulation

As a baseline, we first consider a symmetric case in which the two countries have the same environmental policy, i.e., $t_1 = t_2 = t$ and $F_1 = F_2 = F$ so that $\Psi_j = \Psi$ for $j = 1, 2$. Under symmetry, we focus on how trade liberalization influences global pollution emissions. In the next subsection, we will further investigate the pollution haven effect by allowing for different environmental regulations for different countries.

The results are shown in Figure 3 and summarized in the following proposition:

Proposition 3 *Under symmetric environmental regulations, in the face of trade liberalization (a lower τ), in Country j = 1,2,*

(i) *the cut-off c_{jj} decreases and the cut-off c_{jk} increases, resulting in an increase in the average productivity.*

(ii) *the domestic price p_{jj}^* and the markup of these domestic products μ_{jj}^* decrease because of tougher import competition, while the exporting price p_{jk}^* decreases and the markup of exports μ_{jk}^* increases because of lower exporting costs.*

(iii) *firms (regardless of whether exporters or non-exporters) provide less output for the domestic market $q_{jj}^*(c)$, and then produce less emissions (in both $z_{jj}^*(c)$ and $e_{jj}^*(c)$).*

(iv) *given that* $c_\tau \equiv \frac{\kappa\left(\frac{\tau^\kappa \Psi^\kappa \xi}{1+\tau^\kappa}\right)^{\frac{1}{2+\kappa}}}{\tau(2+\kappa)(1+\tau^\kappa)\Psi}$,

- **a.** *less efficient exporters with* $c_\tau < c < c_{jk}$ *provide more exports* $q^*_{jk}(c)$ *to the foreign market and generate more emissions (in both* $z^*_{jk}(c)$ *and* $e^*_{jk}(c)$*).*
- **b.** *more efficient exporters with* $0 < c < c_\tau$ *provide less exports* $q^*_{jk}(c)$ *to the foreign market and generate less emissions (in both* $z^*_{jk}(c)$ *and* $e^*_{jk}(c)$*).*

Proposition 3(i) vividly conveys the argument of Melitz and Ottaviano (2008). In the presence of lower trade costs, non-exporters encounter keener competition from foreign competitors that forces inefficient firms to leave the market and decreases the cut-off c^*_{jj}. Because only efficient firms with relatively low costs survive, trade liberalization increases the average productivity (a lower $\bar{c}$) in each country. Moreover, because it is easier to assess the foreign market with lower trade costs, trade liberalization favors exporters, resulting in an increase in the cut-off c_{jk}. Note that *this selection effect* leads trade liberalization to be favorable to the global environment. Inefficient firms with higher costs, as stressed in Section 2, rely on more emissions to produce goods and have higher pollution densities, and trade liberalization forces inefficient non-exporters with higher pollution densities to exit the market. This favorable environmental effect, as will be shown later, is more pronounced as the pro-competitive effect of endogenous markups is taken into account. As a result, trade liberalization can decrease, rather than increase, global pollution emissions.

As for the domestic market, import pressure brings tougher competition into the domestic market, which on the one hand, pulls down the domestic price p^*_{jj} and, on the other hand, lowers the markups μ^*_{jj} in the domestic market. Moreover, import competition lowers the residual demand of firms in Country j, and therefore, firms (regardless of whether exporters or non-exporters) reduce their output $q^*_{jj}(c)$ for the domestic market, which lowers the corresponding emission inputs $z^*_{jj}(c)$ (including illegal emissions $e^*_{jj}(c)$).

As for the international market, trade liberalization reduces exporting costs, which on the one hand, decreases the exporting prices p^*_{jk} and, on the other hand, raises the markup μ^*_{jk} of these exports. Interestingly, Propositions 3(iv) indicate that firms with different costs have different responses of output and emissions to trade liberalization even though they are within the group of exporters. While the markups of all exporters increase, the more efficient firms raise their markups more than the less efficient exporters. Due to relatively high markups, like non-exporters, more efficient exporters with costs $0 < c < c_\tau$ decrease their exports $q^*_{jk}(c)$ and emission inputs (in both $z^*_{jk}(c)$ and $e^*_{jk}(c)$). In the face of trade liberalization, these efficient exporters exhibit an extensive margin response in the sense that the mass of exporters (c_{jk}) increases but the output of each exporter ($q^*_{jk}(c)$) decreases. As for those less efficient exporters, relatively low markups induce them to export more goods to the foreign market ($q^*_{jk}(c)$) at lower prices.[11] In order to intensively use emissions ($z^*_{jk}(c)$) to support their high

[11] Mathematically, prices decrease less for more efficient exports (with lower costs $0 < c < \frac{c_\tau}{2}$) but decrease more for

output, the less efficient exporters tend to increase their illegal emissions ($e^*_{jk}(c)$) that lower the use cost of the polluting input. Under environmental regulations, trade liberalization seems to favor less efficient exporters in the sense that not only does the mass of less efficient exporters expand but the output of each exporter also increases.

The distinctive responses of exporters provide a new insight into the recent literature on the environment and trade. In the absence of the pro-competitive effect, Yokoo (2009) and Bajona et al. (2012) show that trade liberalization always favors exporters so that low trade costs increase the output and emissions of all exporters (even though their productivities are different), but decrease those of non-exporters. Instead, we show that in the face of trade liberalization, the different responses appear not only between non-exporters and exporters but also among the exporters. By shedding light on the importance of endogenous markups, this ambiguity affects the scale and selection effects of trade liberalization, giving rise to a favorable impact on the global environment. Thus, we have:

Proposition 4 *In response to trade liberalization, although the world-wide output* $Q^*_w = Q^*_1 + Q^*_2$ *unambiguously increases, the global pollution emissions* $Z^*_w = Z^*_1 + Z^*_2$ *do not necessarily increase.*

In neoclassical trade models, Copeland and Taylor (1994, 1995) and Antweiler et al. (2001) find that due to the scale effect, there is a positive link between the openness to trade and global pollution emissions. Greater openness to trade stimulates output and hence generates more pollution for the whole world. By applying the setting of Melitz (2003), Yokoo (2009) and Bajona et al. (2012) also confirm this positive relationship. The scale effect still dominates, although the trade-induced selection effect raises the average productivity in both the domestic and foreign markets, which translates into a reduction in global pollution by eliminating the highest cost, most polluting firms. In our model, on the one hand, the selection effect eliminates inefficient firms with higher pollution densities. On the other hand, the pro-competitive effect leads trade liberalization to have an unambiguous effect on exporters' emissions. Both reinforce the negative effect of trade on global pollution emissions. Once the scale effect is offset, trade liberalization can decrease, rather than increase, global pollution emissions, breaking the trade-off between output and pollution.

The ambiguous effect on global pollution is supported by mixed empirical findings, as noted in the Introduction. The favorable environmental effect of free trade is also similar to that in recent studies that endogenize abatement technology. Baldwin and Ravetti (2014), Forslid et al. (2014), and Kreickemeier and Richter (2014) consistently show that trade liberalization can be beneficial to the global environment because trade promotes investment in cleaner technology. In a way that differs from their channels, we show that the selection effect is amplified by endogenous markups (i.e., the pro-competitive effect) and hence, trade liberalization can result in a reduction in global pollution emissions.

less efficient exports (with higher costs $\frac{c_T}{2} < c < c_{jk}$) in response to trade liberalization.

Although trade liberalization can stimulate the world output and reduce global pollution simultaneously, this "double dividend" is conditional on the cost distribution. If the cost distribution is uniform (i.e., $\kappa = 1$), we can analytically show that there exists a U-shaped relationship between the trade cost and global pollution (see the Appendix). This non-monotonic relationship refers to a *threshold effect* whereby the *status quo* levels of the trade cost are crucial to their effects on global pollution. In the beginning stage of trade liberalization (relatively high levels of initial trade costs), trade openness can decrease, rather than increase, global pollution. By contrast, when the status quo of trade costs has been very low, further strengthening trade openness will result in more pollution for the whole world.

3.3 Pollution Haven Effect

In this subsection, we investigate the pollution haven effect by assuming that Country 1 unilaterally increases the stringency of environmental regulations. To make our point clearer, we concentrate on an increase in the emission tax.[12]

Proposition 5 *In response to an unilateral increase in Country 1's emission tax t_1,*

(i) *in terms of Country 1 (home country), some less efficient exporters become non-exporters (a lower cut-off c_{12}). Let $\hat{\tau} = (\frac{2+\kappa}{2})^{1/\kappa}$.*

  a. *If trade costs are relatively high ($\tau > \hat{\tau}$), some less efficient non-exporters leave the domestic market (a lower cut-off c_{11}), which results in an increase in the average productivity in the country.*

  b. *If trade costs are relatively low ($\tau < \hat{\tau}$), some less efficient firms enter the domestic market (a higher cut-off c_{11}), which results in a decrease in the average productivity in the country.*

(ii) *in terms of Country 2 (foreign country), while some relatively efficient non-exporters become exporters (a higher cut-off c_{21}), some less efficient non-exporters leave the market (a lower c_{22}) which results in an increase in the average productivity.*

When Country 1 unilaterally raises its emission tax t_1, the cost of emissions in the home country becomes higher than that in the foreign country. A higher environmental cost decreases the profits of Country 1's exporters that forces inefficient exporters to become non-exporters (a decrease in the cut-off c_{12}). A higher environmental cost also leads domestic sales to face more competitive imports from Country 2, decreasing the profits of domestic production (for both exporters and non-exporters). Both reduce the expected profits of potential entrants, greatly decreasing the number of entrants (M_1^*) in Country 1. Such an impact is more pronounced if trade costs are relatively low (i.e., $\tau < \hat{\tau}$). It turns out that if the economy is more open (lower trade costs), the number of entrants will decrease

[12] The violation penalty F has similar effects to those of the emission tax t.

more. Because of the lack of competition from entrants M_1^*, inefficient firms can survive in the domestic market (an increase in the cut-off c_{11}), resulting in a decrease in the average productivity in Country 1.[13]

We learn from Propositions 1 and 5 that a more stringent environmental regulation can increase the average productivity of firms in a closed economy but it may decrease the average productivity of firms in an open economy with trade. The outcome in the open economy is in contradiction to the Porter hypothesis which predicts a positive effect on productivity. Our analysis provides an explanation as to why the literature lacks empirical evidence for the Porter hypothesis (see Jaffe et al. 1995; Greenstone et al. 2012).

When Country 1 unilaterally raises its emission tax t_1, firms in Country 2 can produce goods at a relatively low cost. Because the products of Country 2 become more competitive than those of Country 1, the profits of Country 2's exporters increase, which attracts some efficient non-exporters to export their products (i.e., c_{21} increases). In addition, because the competition from Country 1 decreases, the domestic profits of firms in Country 2 also increase. Both raise the expected profits of potential entrants, and therefore, the number of entrants (M_2^*) in Country 2 greatly increases. Due to a large number of entrants, the competition in Country 2 turns out to become tougher, driving less efficient firms to exit the market. Thus, the cut-off c_{22} decreases, and accordingly, the average productivity of surviving firms in Country 2 increases.

Overall, if the emission tax is higher in Country 1 than in Country 2, a higher environmental cost decreases the international competitiveness of exporters and the domestic profits of firms in Country 1, which results in a decrease in the number of firms (N_1^*) and exporters (X_1^*) in Country 1. By contrast, Country 2's international competitiveness increases, giving rise to a positive effect on the profits of firms in Country 2. As a result, in Country 2, the numbers of firms (N_2^*) and exporters (X_2^*) both increase.

Next, we look into the effects of a unilateral increase in t_1 on the output and emissions of firms. Let $\hat{c}_q \equiv \frac{\kappa\left[\Psi^2(1+\rho)/\xi\right]^{-1/(2+\kappa)}}{(2+\kappa)(1-\rho)}$, $\hat{c}_z \equiv \frac{(1-\lambda)(2+\kappa)(1-\rho)-\lambda\kappa}{(1-2\lambda)\kappa}\hat{c}_q$, $\hat{c}_e \equiv \frac{2\lambda[2(1-\rho)+(2-\rho)\kappa](2F-t)+(1-\rho)(2+\kappa)t}{\kappa(8\lambda F+t-4\lambda t)}\hat{c}_q$, and $\hat{\lambda} \equiv 1-\frac{\kappa}{2(1+\kappa)-(2+\kappa)\rho}$. Accordingly, we establish the following proposition:

Proposition 6 *In response to a unilateral increase in Country* 1*'s emission tax* t_1*,*

(i) *in Country* 1*, exporters decrease their exports* $q_{12}^*(c)$ *and emissions (in both* $z_{12}^*(c)$ *and* $e_{12}^*(c)$*) for the foreign market. As for the domestic market,*

a. *if trade costs are high* ($\tau > \hat{\tau}$)*, firms (both exporters and non-exporters) exhibit similar output and emission responses* ($q_{11}^*(c)$*,* $z_{11}^*(c)$*, and* $e_{11}^*(c)$*) with those in autarky (see Lemma 1 and Proposition 2(i)).*

[13] Once firms aim at the domestic market, they still have a no-trade-cost advantage compared to imports.

b. *if trade costs are low ($\tau < \hat{\tau}$), firms unambiguously increase their output $q_{11}^*(c)$ for the domestic market. Firms with higher costs ($c > \hat{c}_z$) increase their total $z_{11}^*(c)$ and illegal emissions $e_{11}^*(c)$. Firms with lower costs ($c < \hat{c}_z$), however, may decrease their total emissions $z_{11}^*(c)$ but increase illegal emissions $e_{11}^*(c)$, provided that the production is less polluting-input intensive ($\lambda < \hat{\lambda}$).*

(ii) *in Country 2, exporters increase their exports $q_{21}^*(c)$ and emissions (in both $z_{21}^*(c)$ and $e_{21}^*(c)$) for the foreign market. By contrast, firms (both exporters and non-exporters) decrease their output $q_{22}^*(c)$ and emissions (in both $z_{22}^*(c)$ and $e_{22}^*(c)$) for the domestic market.*

A higher emission tax raises the production cost for firms in Country 1, which decreases (increases) the international competitiveness of Country 1's (2's) exporters. Thus, the exports of Country 1 ($q_{12}^*(c)$) decrease but those of Country 2 ($q_{21}^*(c)$) increase. In response to less (more) output of exports, Country 1's (2's) exporters use less (more) polluting input, generating less (more) emissions regardless of whether total $z_{12}^*(c)$ ($z_{21}^*(c)$) or illegal emissions $e_{12}^*(c)$ ($e_{21}^*(c)$).

In terms of the domestic market, because competition from Country 1 decreases, in Country 2 a lot of entrants are attracted to enter their own market. A large increase in entrants (M_2) leads the individual firm in Country 2 to decrease its output $q_{22}^*(c)$ and emissions (in both $z_{22}^*(c)$ and $e_{22}^*(c)$) for its own country's market. The effects are more complicated in Country 1's market, depending the degree of openness to trade. If the world economy is not so open to trade ($\tau > \hat{\tau}$), the consequences reduce to those in autarky, as shown in Lemma 1 and Proposition 2(i). In a way that differs from the autarkic economy, if the world economy is highly open ($\tau < \hat{\tau}$), a higher emission tax unambiguously leads Country 1's firms (both exporters and non-exporters) to offer more output $q_{11}^*(c)$ to their own market.

A more stringent environmental regulation, as shown in Proposition 5, reduces the expected profits of potential entrants and thus decreases the number of entrants (M_1^*) in Country 1. Without the competition from entrants, individual firms in Country 1, regardless of whether exporters or non-exporters, will provide more output $q_{11}^*(c)$ to the domestic market. Nevertheless, firms with distinct costs have different emission strategies to support the increase in output. Given that firms with higher costs ($c > \hat{c}_z$) rely on more polluting inputs, they will more intensively use emissions to support their high output. By contrast, provided that the production is less polluting-input intensive ($\lambda < \hat{\lambda}$), efficient firms with lower costs ($c < \hat{c}_z$) will tend to use less emissions $z_{11}^*(c)$ associated with more illegal emissions $e_{11}^*(c)$ to support their high output. These firms give rise to increased production efficiency via non-compliance with the environmental regulation. Again, the trade-off between output and emissions may not exist for these efficient firms ($c < \hat{c}_z$).

Proposition 7 *In response to a unilateral increase in Country 1's emission tax t_1, the output (Q_1^*) and emissions (Z_1^*) in Country 1 decrease while the output (Q_2^*) and emissions (Z_2^*) in Country 2 increase,* *resulting in a reduction in the world-wide output ($Q_w^* = Q_1^* + Q_2^*$) and global pollution emissions ($Z_w^* = Z_1^* + Z_2^*$).*

If Country 1's environmental regulation is more stringent, the aggregate output and pollution both decrease in this country. On the contrary, because Country 2 becomes more competitive and exports more goods to the international market, the aggregate output and pollution increase in the country with a less stringent environmental regulation. Nevertheless, once any country unilaterally increases the stringency of environmental regulations, global environmental quality can be improved (a decrease in global pollution emissions, Z_w^*) although the world-wide output (Q_w^*) is also reduced accordingly. Proposition 7 potentially points out that, since global environmental quality is a public good, any country that implements a stricter environmental regulation to provide such a public good will suffer a loss of international competitiveness. Our results confirm the validity of the pollution haven effect. A few recent studies, as noted in Levinson and Taylor (2008), have demonstrated statistically significant pollution haven effects by using panels of data and industry or country fixed effects.

4 Welfare Analysis

We now turn to the welfare analysis. Based on (1), (2) and (18), we derive the social welfare of Country $j = 1, 2$ below from the summation of consumers' utility:

$$\begin{aligned} SW_j = & \left[\bar{q}_0 + w + t_j R_j + \frac{F_j (E_j)^2}{Z_j} - \int_0^{c_{jj}} p_{jj}(c) q_{jj}(c) dc - \int_0^{c_{kj}} p_{kj}(c) q_{kj}(c) dc \right] + \alpha \left[\int_0^{c_{jj}} q_{jj}(c) dc + \int_0^{c_{kj}} q_{kj}(c) dc \right] \\ & - \frac{\beta}{2} \left[\int_0^{c_{jj}} q_{jj}^2(c) dc + \int_0^{c_{kj}} q_{kj}^2(c) dc \right] - \frac{\gamma}{2} \left[\int_0^{c_{jj}} q_{jj}(c) dc + \int_0^{c_{kj}} q_{kj}(c) dc \right]^2 - h(Z_j). \end{aligned} \tag{37}$$

In the two-country model, we study the optimal environmental (emission) taxation in relation to both cooperative (tax harmonization) and non-cooperative (tax competition). In particular, we examine the interaction between trade liberalization and optimal emission taxation and its consequences for global pollution emissions.

It is difficult (if not impossible) to analytically perform this welfare analysis. We thus perform a numerical analysis by parameterizing the model according to the convention in the trade literature. First, we assume that labor and emission inputs have equal shares in the production of differentiated goods, i.e., $\lambda = 1/2$. These firms also share the same fixed cost that is normalized to unity, $f = 1$. Moreover, we simply set the penalty rate for illegal emissions as $F = 1$ which meets the requirement whereby the penalty rate is larger than the emission tax rate t. In terms of the Pareto distribution, the lower bound of productivity is $1/c_m = 0.01$; the value of c_m is large enough so that cut-offs are interior. The skewness of the distribution is set as $\kappa = 3$ which is within a reasonable range (see Bernard et al., 2003 and Crozet and Koenig, 2010).[14] As for the utility derived from consumption, we normalize $\beta = 1$ and $\gamma = 1$. Moreover, we set $\alpha = 100$ to scale the demand for differentiated goods in order to have an appropriate scale of the equilibrium output and emissions in the model. Finally, we assume a specific functional form for the disutility of consumers caused by the pollution externality: $h(Z) = \delta Z^{\sigma}$, where δ is the preference weight relative to consumption and $\sigma > 1$ measures the convexity of the disutility function. For simplicity, we set $\delta = 0.1$ and $\sigma = 1.1$ which satisfy the increasingly convex disutility of pollution.

Under emission tax harmonization, we derive the optimal cooperative emission tax, denoted by t^o, by maximizing the joint welfare of both symmetric countries that share an identical environmental regulation. In addition, we examine the equilibrium emission tax, denoted by t^e, under a Nash tax competition.

Figure 5 shows the joint welfare-maximizing tax rate t^o under tax harmonization and the equilibrium tax rate t^e under tax competition as trade costs fall. Figure 6 shows the global pollution emissions Z_w^o under tax harmonization and global pollution emissions Z_w^e under tax competition as trade costs fall. The main results are summarized as follows:

Result 1. *Under the emission tax harmonization,*

(i) *the optimal cooperative emission tax (t^o) has a U-shaped relationship with trade costs (τ), and*

(ii) *trade liberalization unambiguously decreases the global pollution (Z_w^o).*

As shown in Figure 5, the joint welfare maximizing emission tax rate t^o decreases first and then increases as trade become liberalized (lower trade costs τ). Proposition 4 indicates that trade liberalization may either increase or decrease the global pollution even though it unambiguously increases the world-wide output. Since the joint welfare decreases with the global pollution, the optimal emission tax simply follows a similar pattern. As a result, the optimal emission tax has a U-shaped relationship with trade costs. This implies that an extremely low trade cost may end up with more global pollution emissions which call for a higher emission tax. More interestingly, Figure 6 shows that lower trade costs unambiguously decrease global pollution emissions, provided that the two countries cooperate to design a harmonized environmental tax policy. Lower trade costs increase the global consumption and this leads pollution to become more important for the joint welfare. Thus, to maximize the joint welfare, the optimal taxation should be more aggressive to lower the global pollution as trade costs are lower (trade liberalization is higher).

Result 2. *Under the Nash equilibrium of tax competition,*

(i) *the equilibrium emission tax (t^e) has a U-shaped relationship with trade costs (τ), and*

[14] Crozet and Koenig (2010) estimate the skewness of the Pareto distribution in the cost of French firms, showing that κ is between 1.34 and 4.43. By using data for U.S. firms, Bernard et al. (2003) estimate the skewness as $\kappa = 3.6$.

(ii) *trade liberalization may either decrease or increase the global pollution (Z_w^e).*

The relationship between t^e and τ under tax competition is similar to the relationship between t^o and τ under tax harmonization, but trade liberalization no longer necessarily reduces the global pollution under the tax competition equilibrium.

As shown in Figure 5, compared to the joint welfare maximizing one, both countries levy a *lower* emission tax under tax competition in order to induce more output in their own country so that their residents can enjoy more consumption without incurring trade costs. For this reason, the global pollution is higher under tax competition as shown in Figure 6. Under a non-cooperative Nash equilibrium, each country, taking the rival country's emission tax as given, balances the positive welfare effect of the emission tax (i.e., reducing emissions for its own country) and the negative effect of the emission tax (i.e., decreasing output and hence increasing the burden of trade costs for its own country). Because both countries are concerned with their own welfare levels, a U-shaped relationship between trade costs and the equilibrium emission tax is a simple mapping to an inverted U-shaped relationship between trade costs and global pollution emissions. Under tax competition, both countries are concerned that a higher pollution tax will harm the production and lower the international competitiveness. When trade costs are lower, the unfavorable effects become stronger even though consumption increases as a response. This leads both countries to lower their pollution taxes and tolerate more pollution. The effect, however, is limited. When trade costs are reduced to a very low level, consumption turns out to become very high but overwhelming pollution dramatically lowers the social welfare (due to the increasing marginal disutility of pollution). Under this situation, both countries will raise their emission taxes in order to alleviate the disutility caused by pollution. This causes an downturn in the global pollution to decrease after reaching a maximum level, as shown in Figure 6.

At the national level, the standard optimal policy is to internalize environmental externalities. At the international level, the environmental issue becomes more complicated because the burden of environmental externalities, as shown above, is associated with the pressure of international competition. The authority to formulate and enforce environmental policies usually exists only at the national level, whereas most international trade agreements do not include any provisions for environmental protection. Results 1 and 2 suggest that the cooperative optimal environmental regulation is always a better way to decrease the impact of trade liberalization. Our result provides theoretical support for practical international agreements dealing with various environmental issues, such as multilateral environmental agreements (MEAs). The World Trade Organization (WTO), via the Doha Development Agenda, has also made provision for environmental protection and preservation to decrease global pollution emissions.

5 Conclusion

In this paper, we have developed a trade and environmental model with heterogeneous firms and endogenous markups. We have shown that firms with distinctive productivities respond to a unified environmental regulation differently, which changes the market competition structure within a country and across countries. We have also disentangled the interaction effects of environmental regulations and trade liberalization and performed the welfare analysis under both environmental (emission) tax harmonization and tax competition.

Our analysis has shown that in a closed economy, a more stringent environmental regulation shifts production away from less efficient firms toward more efficient firms with lower costs, resulting in a rise in the average productivity of the market. While efficient firms are favored by a stricter environmental regulation, they may produce more emissions by expanding their output levels if their production is more natural resource dependent. Non-compliance with the environmental regulation provides a black market for these firms to escape from the regulation and maintain their competitiveness.

In an open economy with two symmetric countries, trade liberalization can not only decrease global pollution emissions but also increase global output. This breaks the trade-off between the global output and environmental quality. If the two countries are asymmetric in terms of their environmental regulations, we confirm the pollution haven effect whereby output and pollution shift from one country to the other with loose environmental regulations. If a country unilaterally raises its emission tax, both its total output and average productivity decrease. Our results have revealed that a more stringent environmental regulation increases the average productivity of firms in a closed economy but it decreases the average productivity of firms in a open economy with substantially low trade costs. This ambiguity provides an explanation as to why the literature lacks empirical evidence for the Porter hypothesis.

Our welfare analysis has indicated that there is a U-shaped relationship between the optimal emission tax and the openness to trade (the trade cost) regardless of whether under tax harmonization or tax competition. The U-shaped relationship implies that lower trade costs may end up with more global pollution emissions which call for a higher emission tax. Trade liberalization unambiguously decreases global pollution emissions under tax harmonization but it may increase global pollution emissions under tax competition. It is always better for the whole world to fight pollution by cooperatively designing a harmonized environmental policy.

A natural extension along this research line would be to re-examine the interaction effects of environmental regulations and trade liberalization in the case with transboundary pollution, as in Copeland and Taylor (1995). To this end, we need to account for the interaction between consumption and pollution externalities in the utility of consumers. Another avenue for future work would be to introduce investments in abatement technology, followed by the recent studies of Forslid et al. (2014), Kreickemeier and Richter (2014), and Baldwin and Ravetti (2014). By taking the abatement technology effect into account, we expect that the favorable effect of trade liberalization on the global environment will be reinforced, because a larger production scale can support more abatement investment for exporters, and in turn lower their pollution densities. It is also interesting to see what will happen if environmental externalities are not only directly related to the damage to the household's amenities but also indirectly related to the harm done to the firms' factor productivities (see, for example, Bovenberg and Smulders 1995). The detrimental impacts of environmental production externalities, on the one hand, affect the market structure (given that the impacts differ for firms with various production costs) within a country and, on the other hand, govern the international competitiveness across countries, which results in different interaction effects of environmental regulations and trade liberalization.

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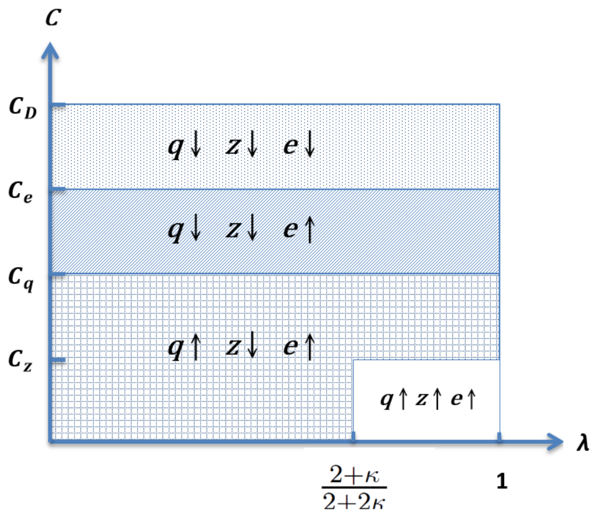

Figure 1: Effects of increasing the emission tax t

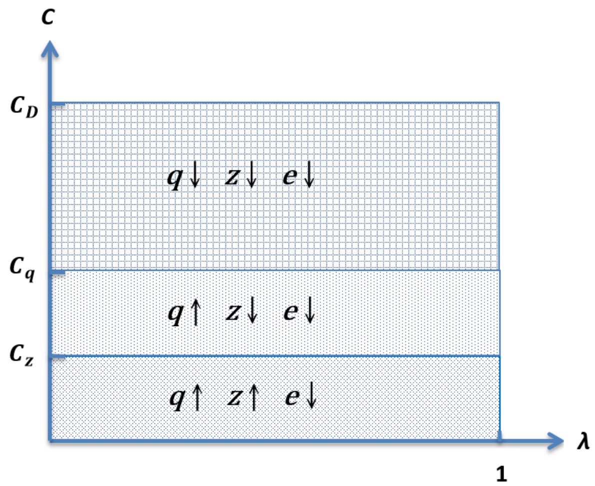

Figure 2: Effects of increasing the penalty for illegal emissions F

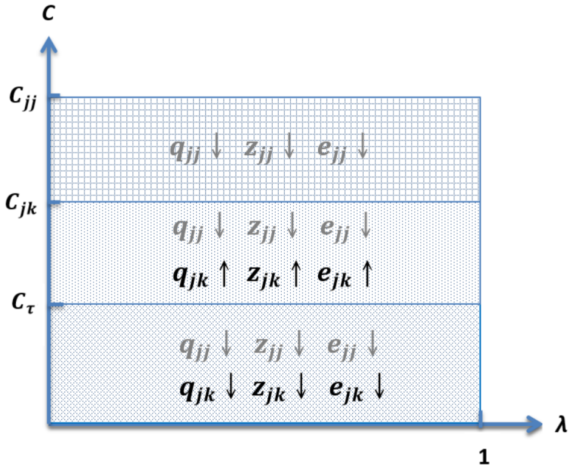

Figure 3. Effect of lower trade costs τ

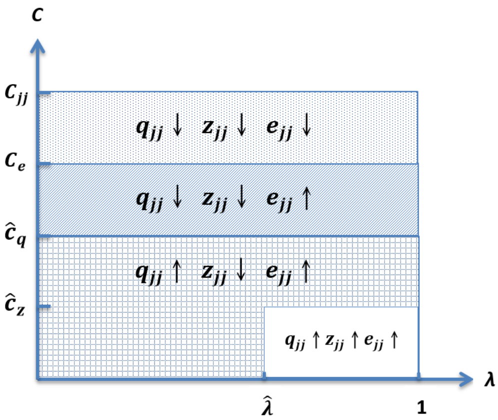

Figure 4a: Effects of increasing the emission tax t when $\tau > \hat{\tau}$

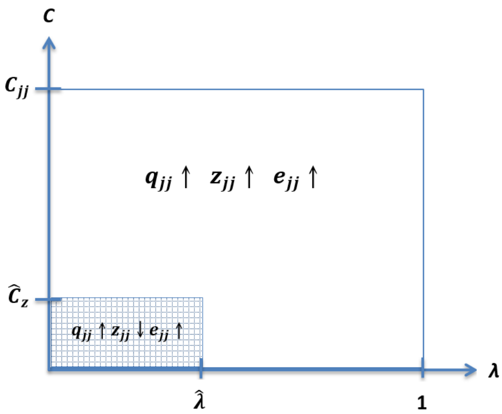

Figure 4b: Effects of increasing the emission tax t when $\tau < \hat{\tau}$

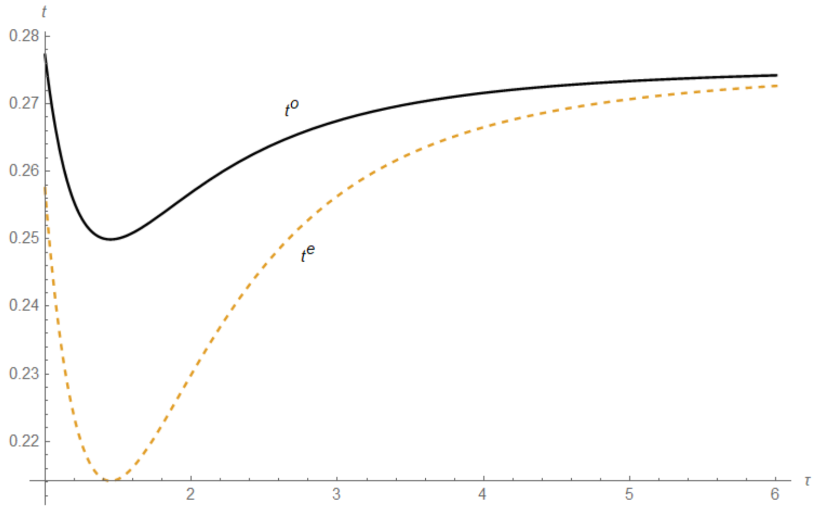

Figure 5: Optimal tax t^o and equilibrium tax t^e

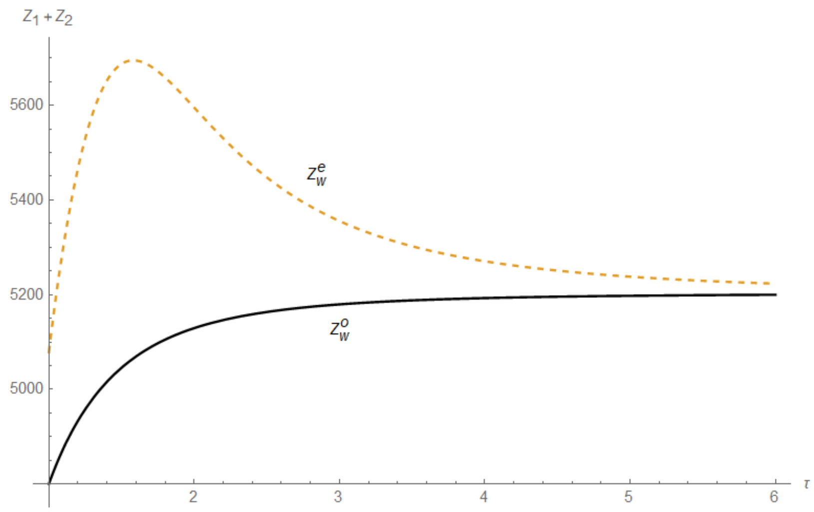

Figure 6: Global pollution under tax harmonization Z_w^o and tax competition Z_w^e

Appendix

(A major portion of the Appendix is not intended for publication.)

Proof of Proposition 1

Given that $\Psi(t,F) = \eta[\chi(t,F)]^{\lambda}$ and $\chi(t,F) = t\left(1 - \frac{t}{4F}\right)$, we can easily derive that $\frac{d\Psi}{dt} = \frac{\partial\Psi}{\partial\chi}\frac{\partial\chi}{\partial t} > 0$ and $\frac{d\Psi}{dF} = \frac{\partial\Psi}{\partial\chi}\frac{\partial\chi}{\partial F} > 0$. Thus, Ψ is an increasing function of t and F. It follows from (20) that the cost cut-off c_D decreases with Ψ and hence decreases with t and F, as well. A lower cost cut-off c_D implies a higher average productivity of firms because $\bar{c} = \frac{\int_0^{c_D} c * g(c)dc}{\int_0^{c_D} g(c)dc} = \frac{\kappa c_D}{1+\kappa}$.

From (12) and (20), we derive:

$$\frac{dp^*(c)}{d\Psi} = \frac{\partial p^*(c)}{\partial\Psi} + \frac{\partial p^*(c)}{\partial c_D}\frac{\partial c_D}{\partial\Psi} = \frac{1}{2}\left(c + \frac{c_D\kappa}{2+\kappa}\right) > 0,$$

which implies that prices increase with t or F. Moreover, more efficient firms with lower c increase their prices less. From (16), it is obvious that the markup $\mu^*(c)$ decreases with t and F for all $c < c_D$.

From (20) and (22), we have:

$$\frac{dN^*}{d\Psi} = \frac{\partial N^*}{\partial\Psi} + \frac{\partial N^*}{\partial c_D}\frac{\partial c_D}{\partial\Psi} = -\frac{2\kappa(1+\kappa)\alpha\beta}{c_D(2+\kappa)\Psi^2\gamma} < 0,$$

implying that the number of surviving firms N^* decreases with t and F. In addition, (11) and (20) allow us to derive:

$$\frac{dQ^*}{d\Psi} = \frac{\partial Q^*}{\partial\Psi} + \frac{\partial Q^*}{\partial c_D}\frac{\partial c_D}{\partial\Psi} = -\frac{c_D\Psi}{(2+\kappa)\gamma} < 0.$$

From (20) and (23), we obtain:

$$\begin{aligned}\frac{dZ^*}{d\Psi} &= \frac{\partial Z^*}{\partial\Psi} + \frac{\partial Z^*}{\partial c_D}\frac{\partial c_D}{\partial\Psi} \\ &= -\frac{\kappa c_D\left\{\alpha[2+(1-\lambda)\kappa] - [2+(1-2\lambda)\kappa]\, c_D\Psi\right\}}{(2+\kappa)^2\gamma}\left(\frac{\eta}{\Psi}\right)^{1/\lambda} < 0.\end{aligned}$$

The two equations above indicate that the economy-wide output Q^* and emissions Z^* decreases with t and F. From (20) and (24), we have an ambiguous effect on illegal emissions:

$$\begin{aligned}\frac{dE^*}{dt} &= \frac{\partial E^*}{\partial t} + \frac{\partial E^*}{\partial\Psi}\frac{d\Psi}{dt} + \frac{\partial E^*}{\partial c_D}\frac{\partial c_D}{\partial\Psi}\frac{d\Psi}{dt} \\ &= \frac{\lambda\kappa c_D\Psi\left[t(2+\kappa)(\alpha - c_D\Psi) + 2\lambda\kappa(2F-t)(\alpha - 2c_D\Psi)\right]}{2F(4F-t)(2+\kappa)^2\gamma}\left(\frac{\eta}{\Psi}\right)^{1/\lambda}.\end{aligned}$$

which shows $\frac{dE^*}{dt} > 0$ for $\alpha > 2c_D\Psi$. However, for $c_D\Psi < \alpha < 2c_D\Psi$, we have that $\frac{dE^*}{dt} > 0$ is still true for higher taxes $t > \frac{2F}{1 - \frac{(2+\kappa)(\alpha - c_D\Psi)}{2\lambda\kappa(\alpha - 2c_D\Psi)}}$ while $\frac{dE^*}{dt} < 0$ for small taxes $t < \frac{2F}{1 - \frac{(2+\kappa)(\alpha - c_D\Psi)}{2\lambda\kappa(\alpha - 2c_D\Psi)}}$.

Finally, we derive the effect of a penalty on E^* as follows:

$$\begin{aligned}\frac{dE^*}{dF} &= \frac{\partial E^*}{\partial F} + \frac{\partial E^*}{\partial\Psi}\frac{d\Psi}{dF} + \frac{\partial E^*}{\partial c_D}\frac{\partial c_D}{\partial\Psi}\frac{d\Psi}{dF} \\ &= -\frac{t\lambda\kappa c_D\Psi\left\{\alpha[4F(2+\kappa) - t\lambda\kappa] - c_D\Psi[4F(2+\kappa) - 2t\lambda\kappa]\right\}}{2F^2(4F-t)(2+\kappa)^2\gamma}\left(\frac{\eta}{\Psi}\right)^{1/\lambda} < 0,\end{aligned}$$

given that $\alpha > c_D\Psi$, $F > t$ and $0 < \lambda < 1$.

Proof of Lemmas 1 and 2 and Proposition 2

In terms of Lemma 1, we differentiate (13) with respect to t and obtain the output of individual firms:

$$\frac{dq^*(c)}{dt} = \frac{\partial q^*(c)}{\partial \Psi}\frac{\partial \Psi}{\partial \chi}\frac{\partial \chi}{\partial t} = \frac{\{\kappa c_D^* - c\,(2+\kappa)\}}{2\,(2+\kappa)\,\beta}(\lambda\eta\chi^{\lambda-1})\frac{\partial \chi}{\partial t},$$

where $\frac{\partial \chi}{\partial t} > 0$. Thus, we have:

$$\frac{dq^*(c)}{dt} \gtreqqless 0 \text{ for } c \lesseqqgtr \frac{\kappa c_D}{2+\kappa} \equiv c_q,$$

where $0 < c_q < c_D$ because $\kappa > 1$. In response to a higher t, the surviving firms with lower costs $0 < c < c_q$ increase their output levels and the others with higher costs $c_q < c < c_D$ decrease their output levels. Similarly, by differentiating (14) with respect to t, we obtain the optimal emission input:

$$\begin{cases} \text{If } \frac{2+\kappa}{2+2\kappa} < \lambda < 1, \ \frac{dz^*(c)}{dt} \gtreqqless 0 \text{ for } c \lesseqqgtr \frac{2+\kappa-2\lambda(1+\kappa)}{(1-2\lambda)(2+\kappa)} c_D \equiv c_z, \\ \text{If } 0 < \lambda < \frac{2+\kappa}{2+2\kappa}, \ \frac{dz^*(c)}{dt} < 0 \text{ for all } c < c_D, \end{cases}$$

where $0 < c_z < c_D$. Regarding illegal emissions, we differentiate (17) with respect to t and obtain:

$$\frac{de^*(c)}{dt} \gtreqqless 0 \text{ for } c \lesseqqgtr \frac{4\lambda\,(1+\kappa)\,(2F-t) + (2+\kappa)\,t}{(2+\kappa)\,(8\lambda F + t - 4\lambda t)} c_D \equiv c_e,$$

where $0 < c_e < c_D$ because $0 < \lambda < 1$, $\kappa > 1$ and $F > t$.

Finally, it can be easily verified that $0 < c_z < c_q < c_e < c_D$ for $\frac{2+\kappa}{2+2\kappa} < \lambda < 1$. However, for $0 < \lambda < \frac{2+\kappa}{2+2\kappa}$, we have $0 < c_q < c_e < c_D < c_z$.

In terms of Lemma 2, by differentiating the output in (13) and emissions in (14) with respect to F, respectively, we can obtain the cost cut-offs c_q and c_z: $\frac{dq^*(c)}{dF} \gtreqqless 0$ for $c \lesseqqgtr c_q$, and $\frac{dz(c)}{dF} \gtreqqless 0$ for $c \lesseqqgtr c_z$. This implies that in response to a higher penalty F the surviving firms with lower costs $0 < c < c_q$ increase their output and the others with higher costs $c_q < c < c_D$ decrease their output. Also, as the penalty F increases the surviving firms with lower costs $0 < c < c_z$ increase their emissions and the others with higher costs $c_z < c < c_D$ decreases their emissions, which holds for $0 < \lambda < 1$.

By focusing on the effect on illegal emissions, we differentiate the illegal emissions in (17) with respect to F and obtain:

$$\frac{de^*(c)}{dF} = -\frac{2^{1-2\lambda}t^{2\lambda}\left[\frac{\lambda}{(1-\lambda)}\right]^{1-\lambda}(4F\text{-}t)^{2\lambda-2}\left\{2\,(c_D\text{-}c)\,(2\text{+}\kappa)F\text{+}[(1\text{-}\lambda)c_D\text{+}\lambda c\,(2\text{+}\kappa)]t\right\}\eta c}{(2+\kappa)\,\beta F^{1+2\lambda}} < 0,$$

where $2\,(c_D - c)\,(2+\kappa)F + [(1-\lambda)c_D + \lambda c\,(2+\kappa)]t > 0$ because $0 < c < c_D$, $0 < \lambda < 1$, $\kappa > 1$ and $F > t$. Accordingly, we have $\frac{de^*(c)}{dF} < 0$ for all $0 < c < c_D$.

Proof of Proposition 3

Assume that both countries have the same environmental regulation, i.e., $t_1 = t_2 = t$, $F_1 = F_2 = F$ and $\Psi_1 = \Psi_2 = \Psi$. Thus, we have:

$$c_{jj} = \frac{\left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{\Psi},\ c_{jk} = \frac{\left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{\tau\Psi},$$

$$q^*_{jj}(c) = \frac{\left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}} - c\Psi}{2\beta},\ q^*_{jk}(c) = \frac{\left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}} - c\Psi\tau}{2\beta},$$

$$z^*_{jj}(c) = \frac{\lambda\eta c\left[\left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}} - c\Psi\right]\chi^{-1+\lambda}}{2\beta},\ z^*_{jk}(c) = \frac{\lambda\eta c\left[\left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}} - c\Psi\tau\right]\chi^{-1+\lambda}}{2\beta},$$

$$e^*_{jj}(c) = \frac{\lambda\eta ct\left[\left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}} - c\Psi\right]\chi^{-1+\lambda}}{4F\beta},\ e^*_{jk}(c) = \frac{\lambda\eta ct\left[\left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}} - c\Psi\tau\right]\chi^{-1+\lambda}}{4F\beta},$$

$$p^*_{jj}(c) = \frac{1}{2}\left[\left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}} + c\Psi\right],\ p^*_{jk}(c) = \frac{1}{2}\left[\left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}} + \tau c\Psi\right].$$

for $j = 1, 2$ and $k \neq j$. Moreover, the aggregate variables are given by:

$$Q^*_1 = Q^*_2 = Q^* = \frac{\alpha - \left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{\gamma},$$

$$N^*_1 = N^*_2 = N^* = \frac{2\beta\,(1+\kappa)\left[\alpha - \left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}\right]}{(1+\rho)\left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}\gamma},$$

$$X^*_1 = X^*_2 = X^* = N^*/\rho$$

$$Z^*_1 = Z^*_2 = Z^* = \frac{\kappa\left(1+\frac{\rho}{\tau}\right)\left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}\left[\alpha - \left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}\right]\left[\frac{\lambda}{(1\text{-}\lambda)\chi_j}\right]^{1-\lambda}}{(1+\rho)\,(2+\kappa)\gamma\Psi},$$

$$E^*_1 = E^*_2 = E^* = \frac{t}{2F}Z^*,$$

where we assume that $\alpha > \left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}$ to ensure $N^* > 0$, which also guarantees positive output $Q^* > 0$ and exports $Q^*_{jk} = Q^*_{kj} = \frac{\alpha - \left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{\gamma(1+\tau^\kappa)} > 0$.

To investigate the impacts of trade liberalization (a lower τ), we substitute (32) into (26) and, accordingly, derive the following:

$$\frac{\partial c_{jj}}{\partial \tau} = \frac{\kappa\left(\frac{\Psi^\kappa \tau^\kappa \xi}{1+\tau^\kappa}\right)^{\frac{1}{2+\kappa}}}{(2+\kappa)\,\Psi\tau\,(1+\tau^\kappa)} > 0,$$

$$\frac{\partial c_{jk}}{\partial \tau} = \frac{\kappa\left(\frac{\Psi^\kappa \tau^\kappa \xi}{1+\tau^\kappa}\right)^{\frac{1}{2+\kappa}}}{\tau\,(2+\kappa)\,(1+\tau^\kappa)\,\Psi} < 0.$$

A lower c_{jj} implies a higher average productivity of firms in Country j because $\bar{c}_j = \frac{\int_0^{c_{jj}} c * g(c)dc}{\int_0^{c_{jj}} g(c)dc} = \frac{\kappa c_{jj}}{1+\kappa}$.

Substituting (32) into (28) yields the prices below:

$$p_{jj}^* = \frac{1}{2}\left[\left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}} + c\Psi\right],$$
$$p_{jk}^* = \frac{1}{2}\left[\left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}} + c\Psi\tau\right].$$

By differentiating the prices with respect to τ, we obtain:

$$\frac{\partial p_{jj}^*}{\partial \tau} = \frac{\kappa \Psi^{\frac{\kappa}{2+\kappa}} \xi^{\frac{1}{2+\kappa}}}{2\tau^{\frac{2}{2+\kappa}}(2+\kappa)(1+\tau^\kappa)^{\frac{3+\kappa}{2+\kappa}}} > 0,$$
$$\frac{\partial p_{jk}^*}{\partial \tau} = \frac{1}{2}c\Psi + \frac{\kappa \Psi^{\frac{\kappa}{2+\kappa}} \xi^{\frac{1}{2+\kappa}}}{2\tau^{\frac{2}{2+\kappa}}(2+\kappa)(1+\tau^\kappa)^{\frac{3+\kappa}{2+\kappa}}} > 0.$$

It is clear from these equations that the increases in prices are larger for firms with higher costs c. By differentiating the markups $\mu_{jj}^* = \frac{p_{jj}^*}{c\Psi_j}$ and $\mu_{jk}^* = \frac{p_{jk}^*}{c\Psi_j}$ with respect to τ, it can be easily shown that $\frac{\partial \mu_{jj}^*}{\partial \tau} > 0$ and $\frac{\partial \mu_{jk}^*}{\partial \tau} > 0$ because $c\Psi_j$ is independent of τ.

In addition, differentiating the output of individual firms with respect to τ yields:

$$\frac{\partial q_{jj}^*}{\partial \tau} = \frac{\kappa\left(\frac{\Psi^\kappa \tau^\kappa \xi}{1+\tau^\kappa}\right)^{\frac{1}{2+\kappa}}}{2\tau\beta(2+\kappa)(1+\tau^\kappa)} > 0,$$
$$\frac{\partial q_{jk}^*}{\partial \tau} = \frac{\frac{\kappa\left(\frac{\Psi^\kappa \tau^\kappa \xi}{1+\tau^\kappa}\right)^{\frac{1}{2+\kappa}}}{\tau(2+\kappa)(1+\tau^\kappa)} - c\Psi}{2\beta},$$

By solving $\frac{\partial q_{jk}^*}{\partial \tau} = 0$, we can obtain the critical value: $c_\tau = \frac{\kappa\left(\frac{\Psi^\kappa \tau^\kappa \xi}{1+\tau^\kappa}\right)^{\frac{1}{2+\kappa}}}{\tau(2+\kappa)(1+\tau^\kappa)\Psi} < c_{jk}$ because $\frac{c_\tau}{c_{jk}} = \frac{\kappa}{(2+\kappa)(1+\tau^\kappa)} < 1$. We obtain that $\frac{\partial q_{jk}^*}{\partial \tau} > 0$ for $c < c_\tau$ while $\frac{\partial q_{jk}^*}{\partial \tau} < 0$ for $c > c_\tau$, which implies that, in response to lower trade costs, more efficient firms with $c < c_\tau$ decrease their exports whereas less efficient firms with $c > c_\tau$ increase their exports.

Accordingly, we have:

$$\frac{\partial c_\tau}{\partial \tau} = -\frac{\kappa\left(\frac{\Psi^\kappa \tau^\kappa \xi}{1+\tau^\kappa}\right)^{\frac{1}{2+\kappa}}\left[2+(1+\kappa)(2+\kappa)\tau^\kappa\right]}{2\tau^2(2+\kappa)^2(1+\tau^\kappa)^2\Psi} < 0,$$

indicating that when τ decreases, c_τ increases. Moreover, we have:

$$\frac{\partial z_{jj}^*}{\partial \tau} = \frac{c\lambda\kappa\left(\frac{\Psi^\kappa \tau^\kappa \xi}{1+\tau^\kappa}\right)^{\frac{1}{2+\kappa}}\left(\frac{\lambda}{\chi-\lambda\chi}\right)^{-\lambda}}{2\tau\beta(1-\lambda)(2+\kappa)(1+\tau^\kappa)\chi} > 0,$$
$$\frac{\partial z_{jk}^*}{\partial \tau} = \frac{c\lambda\left(\frac{\lambda}{\chi-\lambda\chi}\right)^{-\lambda}\left[\tau c\eta(2+\kappa)(1+\tau^\kappa)\chi^\lambda - \kappa\left(\frac{\Psi^\kappa \tau^\kappa \xi}{1+\tau^\kappa}\right)^{\frac{1}{2+\kappa}}\right]}{2\tau\beta(\lambda-1)(2+\kappa)(1+\tau^\kappa)\chi},.$$

By solving $\frac{\partial z_{jk}^*}{\partial \tau} = 0$, we show that $\frac{\partial z_{jk}^*}{\partial \tau} > 0$ for $c < c_\tau$ while $\frac{\partial z_{jk}^*}{\partial \tau} < 0$ for $c > c_\tau$. Because $e_{jj}^* = \frac{t}{2F}z_{jj}^*$ and $e_{jk}^* = \frac{t}{2F}z_{jk}^*$, the effect of trade costs τ has the same impact on the amount of illegal emissions e_{jj}^* and e_{jk}^*. (Note that the pollution density of individual firms is independent of trade costs, given that $\frac{z_{jj}^*}{q_{jj}^*} = \frac{z_{jk}^*}{q_{jk}^*} = c\lambda\eta\chi^{-1+\lambda}$.)

Proof of Proposition 4

Under symmetric environmental regulations, we differentiate the aggregate output Q_j^* (where $j = 1, 2$) with respect to trade costs τ and obtain:

$$\frac{\partial Q_j^*}{\partial \tau} = -\frac{\kappa \left(\frac{\Psi^\kappa \tau^\kappa \xi}{1+\tau^\kappa}\right)^{\frac{1}{2+\kappa}}}{\tau\gamma\left(2+\kappa\right)\left(1+\tau^\kappa\right)} < 0.$$

By differentiating the aggregate pollution Z_j^* with respect to τ, we obtain:

$$\frac{\partial Z_j^*}{\partial \tau} = \frac{\lambda^{1-\lambda}\kappa\left[\frac{\Psi^\kappa \tau^\kappa \xi}{1+\tau^\kappa}\right]^{\frac{1}{2+\kappa}} A\left(\chi - \lambda\chi\right)^\lambda}{\gamma\tau^2\chi\left(1-\lambda\right)\left(2+\kappa\right)^2\left(1+\tau^\kappa\right)^2\Psi}$$

where

$$A \equiv \alpha\left\{\left[\kappa(3+\kappa)(\tau\text{-}1)\text{-}2\right]\tau^\kappa\text{-}2\right\} + \left[\frac{\Psi^\kappa \tau^\kappa \xi}{1+\tau^\kappa}\right]^{\frac{1}{2+\kappa}}\left\{2\text{-}\kappa\text{-}\tau^\kappa\left[\kappa\left(4+\kappa\right)\tau\text{-}2\text{-}\kappa\left(3+\kappa\right)\right]\right\}$$

Accordingly, we obtain $\frac{\partial Z_j^*}{\partial \tau} \lesseqgtr 0$ if $A \lesseqgtr 0$.

For $\kappa = 1$, A is reduced to:

$$A = \alpha(4\tau^2 - 6\tau - 2) - \left(\frac{\tau\Psi\xi}{1+\tau}\right)^{\frac{1}{3}}(5\tau^2 - 6\tau - 1).$$

By substituting $\alpha = \left(\frac{\tau\Psi\xi}{1+\tau}\right)^{\frac{1}{3}}$ into the above A, we obtain

$$A\mid_{\alpha=\left(\frac{\Psi\xi}{1+1/\tau}\right)^{\frac{1}{3}}} = -\left(\frac{\tau\Psi\xi}{1+\tau}\right)^{\frac{1}{3}}\left(1+\tau^2\right) < 0.$$

Because $\alpha > \left(\frac{\tau\Psi\xi}{1+\tau}\right)^{\frac{1}{3}}$, for $\tau < 1.78$ which ensures $4\tau^2 - 6\tau - 2 < 0$, we must have $\partial Z_j^*/\partial\tau < 0$. However, for $\tau > 1.78$, we have $\partial Z_j^*/\partial\tau \lesseqgtr 0$ if $\alpha \lesseqgtr \frac{5\tau^2-6\tau-1}{4\tau^2-6\tau-2}\left(\frac{\tau\Psi\xi}{1+\tau}\right)^{\frac{1}{3}}$.

Moreover, the following shows that we have the second derivative $\frac{\partial^2 Z_j^*}{\partial\tau^2} > 0$, for $1 < \tau < 2.97$.

$$\frac{\partial^2 Z_j^*}{\partial \tau^2} = \frac{2\lambda^{1-\lambda}\xi[(1-\lambda)\,\chi]^\lambda B}{27\gamma\tau^2\left(1-\lambda\right)\left(\frac{\tau\Psi\xi}{1+\tau}\right)^{\frac{2}{3}}\left(1+\tau\right)^4\chi}$$

where

$$B \equiv \alpha(5 + 18\tau + 29\tau^2 - 12\tau^3) - \left(\frac{\tau\Psi\xi}{1+\tau}\right)^{\frac{1}{3}}(2 + 9\tau + 32\tau^2 - 15\tau^3).$$

Accordingly, we obtain $\frac{\partial^2 Z_j^*}{\partial\tau^2} \gtreqless 0$ if $B \gtreqless 0$. Moreover, by substituting $\alpha = \left(\frac{\tau\Psi\xi}{1+\tau}\right)^{\frac{1}{3}}$ into B, we obtain

$$B\mid_{\alpha=\left(\frac{\Psi\xi}{1+1/\tau}\right)^{\frac{1}{3}}} = 3\left(\frac{\tau\Psi\xi}{1+\tau}\right)^{\frac{1}{3}}\left(1+3\tau-\tau^2+\tau^3\right) > 0.$$

Because $\alpha > \left(\frac{\tau\Psi\xi}{1+\tau}\right)^{\frac{1}{3}}$, for $\tau < 2.97$ which ensures $5+18\tau+29\tau^2-12\tau^3 > 0$, we must have $\partial^2 Z_j^*/\partial\tau^2 > 0$. In other words, the slope $\partial Z_j^*/\partial\tau$ increases during $1.78 < \tau < 2.97$, and the following shows that $\partial Z_j^*/\partial\tau > 0$ at $\tau = 2.97$ if $\alpha > 1.49\left(\Psi\xi\right)^{\frac{1}{3}}$.

$$\left[\frac{5\tau^2-6\tau-1}{4\tau^2-6\tau-2}\left(\frac{\tau\Psi\xi}{1+\tau}\right)^{\frac{1}{3}}\right]\mid_{\tau=2.97} = 1.49\left(\Psi\xi\right)^{\frac{1}{3}}$$

Besides, by substituting $\alpha = 1.49\,(\Psi\xi)^{\frac{1}{3}}$ into A, we have

$$A\mid_{\alpha=\left(\frac{\tau\Psi\xi}{1+\tau}\right)^{\frac{1}{3}}} = (\Psi\xi)^{\frac{1}{3}}\left[-2.98 - 8.94\tau + 5.96\tau^2 + \left(\frac{\tau}{1+\tau}\right)^{\frac{1}{3}}(1+6\tau-5\tau^2)\right] > 0$$

for any $\tau > 2.97$. Accordingly, for $\alpha > 1.49\,(\Psi\xi)^{\frac{1}{3}}$, which implies a relatively low Ψ, we may show the following U-shaped relationship between global pollution Z_w^* and trade costs τ:

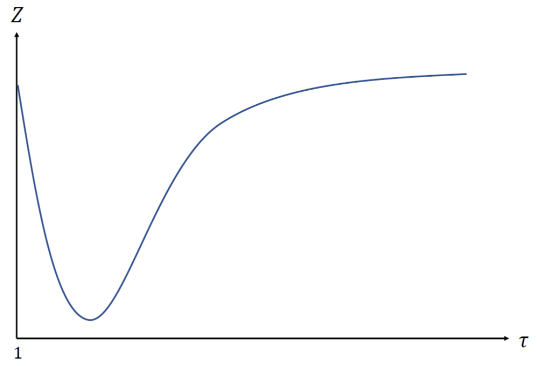

Figure 7: Global emissions Z_w^* and trade costs τ

Proof of Proposition 5

Suppose that Country 1 unilaterally increases its emission tax, say t_1. Thus, differentiating the cost cut-offs of surviving firms and exporters with respect to t_1 yields:

$$\frac{\partial c_{11}}{\partial t_1} = \frac{\partial c_{11}}{\partial \Psi_1}\frac{\partial \Psi_1}{\partial t_1} = \frac{\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}\left[2-(2+\kappa)\rho\right]}{(2+\kappa)(\rho-1)\Psi^2}\frac{\partial \Psi_1}{\partial t_1} \gtreqless 0 \;\text{ if } \tau \lesseqgtr \hat{\tau},$$

$$\frac{\partial c_{12}}{\partial t_1} = \frac{\partial c_{12}}{\partial \Psi_1}\frac{\partial \Psi_1}{\partial t_1} = \frac{(2+\kappa-2\rho)\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{(2+\kappa)(\rho-1)\tau\Psi^2}\frac{\partial \Psi_1}{\partial t_1} < 0,$$

$$\frac{\partial c_{22}}{\partial t_1} = \frac{\partial c_{22}}{\partial \Psi_1}\frac{\partial \Psi_1}{\partial t_1} = \frac{\kappa\rho\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{(2+\kappa)(\rho-1)\Psi^2}\frac{\partial \Psi_1}{\partial t_1} < 0,$$

$$\frac{\partial c_{21}}{\partial t_1} = \frac{\partial c_{21}}{\partial \Psi_1}\frac{\partial \Psi_1}{\partial t_1} = -\frac{\kappa\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{(2+\kappa)(\rho-1)\tau\Psi^2}\frac{\partial \Psi_1}{\partial t_1} > 0,$$

where $\frac{\partial \Psi_1}{\partial t_1} > 0$ according to the definition of $\Psi_1 = \eta\left[t_1\left(1-\frac{t_1}{4F_1}\right)\right]^\lambda$. From the above equations, we can summarize the following:

$$\begin{cases} \frac{\partial c_{11}}{\partial t_1} > 0 \;\text{ if }\; \tau < \hat{\tau} \\ \frac{\partial c_{11}}{\partial t_1} < 0 \;\text{ if }\; \tau > \hat{\tau} \end{cases},$$
$$\frac{\partial c_{12}}{\partial t_1} < 0,\; \frac{\partial c_{22}}{\partial t_1} < 0 \text{ and } \frac{\partial c_{21}}{\partial t_1} > 0.$$

Thus, we further obtain:

$$\frac{\partial N_1^*}{\partial \Psi_1} = -\frac{2\kappa(1+\kappa)\beta\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{-\frac{1}{2+\kappa}}}{(2+\kappa)\Psi\gamma(1-\rho)^2(1+\rho)}\left\{\alpha\left[1+\rho(\kappa+\rho+\kappa\rho)\right]-\kappa\rho(1+\rho)\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}\right\}<0,$$

$$\frac{\partial X_1^*}{\partial \Psi_1} = -\frac{2\kappa(1+\kappa)\beta\rho\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{-\frac{1}{2+\kappa}}}{(2+\kappa)\Psi\gamma(1-\rho)^2(1+\rho)}\left[\alpha\left(1+\kappa+\kappa\rho+\rho^2\right)-\kappa(1+\rho)\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}\right]<0,$$

$$\frac{\partial N_2^*}{\partial \Psi_1} = \frac{2\kappa(1+\kappa)\beta\rho\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{-\frac{1}{2+\kappa}}}{(2+\kappa)\Psi\gamma(1-\rho)^2(1+\rho)}\left[\alpha(2+\kappa+\kappa\rho)-\kappa\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}(1+\rho)\right]>0,$$

$$\frac{\partial X_2^*}{\partial \Psi_1} = \frac{2\kappa(1+\kappa)\beta\rho\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{-\frac{1}{2+\kappa}}}{(2+\kappa)\Psi\gamma(1-\rho)^2(1+\rho)}\left\{2\alpha\rho+\kappa(1+\rho)\left[\alpha-\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}\right]\right\}>0.$$

Because $\frac{\partial N_1^*}{\partial \Psi_1}$ is decreasing in α and $\frac{\partial N_1^*}{\partial \Psi_1}<0$ at $\alpha=\min\alpha=\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}$, we have $\frac{\partial N_1^*}{\partial \Psi_1}<0$ for all $\alpha>\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}$. Similarly, we can obtain $\frac{\partial X_1^*}{\partial \Psi_1}<0$. Thus,

$$\frac{\left(\frac{\partial N_1^*}{\partial \Psi_1}\mid_{\alpha=\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}\right)}{\frac{2\kappa(1+\kappa)\beta\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{(2+\kappa)\Psi\gamma(1-\rho)^2(1+\rho)}} = -\Psi^{\frac{\kappa}{2+\kappa}}\xi^{\frac{1}{2+\kappa}}(1+\rho)^{-\frac{1}{2+\kappa}}\left(1+\rho^2\right)<0,$$

$$\frac{\left(\frac{\partial X_1^*}{\partial \Psi_1}\mid_{\alpha=\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}\right)}{\frac{2\kappa(1+\kappa)\beta\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{(2+\kappa)\Psi\gamma(1-\rho)^2(1+\rho)}} = -\Psi^{\frac{\kappa}{2+\kappa}}\xi^{\frac{1}{2+\kappa}}(1+\rho)^{-\frac{1}{2+\kappa}}\left(1+\rho^2\right)<0.$$

Because $\frac{\partial N_2^*}{\partial \Psi_1}$ is increasing in α and $\frac{\partial N_2^*}{\partial \Psi_1}>0$ at $\alpha=\min\alpha=\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}$, we have $\frac{\partial N_2^*}{\partial \Psi_1}>0$ for all $\alpha>\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}$. Similarly, we obtain $\frac{\partial X_2^*}{\partial \Psi_1}>0$. Thus,

$$\frac{\left(\frac{\partial N_2^*}{\partial \Psi_1}\mid_{\alpha=\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}\right)}{\frac{2\kappa(1+\kappa)\beta\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{-\frac{1}{2+\kappa}}}{(2+\kappa)\Psi\gamma(1-\rho)^2(1+\rho)}} = 2\Psi^{\frac{\kappa}{2+\kappa}}\xi^{\frac{1}{2+\kappa}}(1+\rho)^{-\frac{1}{2+\kappa}}>0,$$

$$\frac{\left(\frac{\partial X_2^*}{\partial \Psi_1}\mid_{\alpha=\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}\right)}{\frac{2\kappa(1+\kappa)\beta\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{-\frac{1}{2+\kappa}}}{(2+\kappa)\Psi\gamma(1-\rho)^2(1+\rho)}} = 2\Psi^{\frac{\kappa}{2+\kappa}}\xi^{\frac{1}{2+\kappa}}\rho(1+\rho)^{-\frac{1}{2+\kappa}}>0.$$

Proof of Proposition 6

First of all, we differentiate the output $(q_{11}^*, q_{12}^*, q_{22}^*, q_{21}^*)$ with respect to t_1 and obtain:

$$\frac{\partial q_{11}^*}{\partial t_1} = \frac{1}{2\beta}\left[-c + \frac{\kappa\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{(2+\kappa)\Psi(1-\rho)}\right]\frac{\partial\Psi_1}{\partial t_1} \gtreqless 0,$$

$$\frac{\partial q_{12}^*}{\partial t_1} = -\frac{1}{2\beta}\left[\frac{\kappa\rho\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{(2+\kappa)(1-\rho)\Psi} + \tau c\right]\frac{\partial\Psi_1}{\partial t_1} < 0,$$

$$\frac{\partial q_{22}^*}{\partial t_1} = -\frac{\kappa\rho\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{2(2+\kappa)\Psi\beta(1-\rho)}\frac{\partial\Psi_1}{\partial t_1} < 0,$$

$$\frac{\partial q_{21}^*}{\partial t_1} = \frac{\kappa\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{2(2+\kappa)\Psi\beta(1-\rho)}\frac{\partial\Psi_1}{\partial t_1} > 0.$$

Solving $\frac{\partial q_{11}^*}{\partial t_1} = 0$ allows us to have the following critical cost:

$$\hat{c}_q = \frac{\kappa\left[\Psi^2(1+\rho)/\xi\right]^{-1/(2+\kappa)}}{(2+\kappa)(1-\rho)},$$

where $\hat{c}_q < c_{12}$ because $\frac{\hat{c}_q}{c_{12}} = \frac{\kappa\tau}{2+\kappa+2\tau+\kappa\tau} < 1$. Based on these results, we summarize the following:

$$\begin{cases} \frac{\partial q_{11}^*(c)}{\partial t_1} > 0 \quad \text{as } \tau < \hat{\tau} \\ \frac{\partial q_{11}^*(c)}{\partial t_1} \gtreqless 0 \text{ if } c \lesseqgtr \hat{c}_q \quad \text{as } \tau > \hat{\tau} \end{cases},$$
$$\frac{\partial q_{12}^*(c)}{\partial t_1} < 0,\ \frac{\partial q_{22}^*(c)}{\partial t_1} < 0, \text{ and } \frac{\partial q_{21}^*(c)}{\partial t_1} > 0.$$

By differentiating the emissions $(z_{11}^*, z_{12}^*, z_{22}^*, z_{21}^*)$ with respect to t_1, we obtain:

$$\frac{\partial z_{11}^*}{\partial t_1} = \frac{\lambda c\Psi(2F\text{-}t)\left(\frac{\Psi}{\eta}\right)^{-\frac{2}{\lambda}}}{4F\beta(2+\kappa)(1\text{-}\rho)}\left\{c\Psi(1\text{-}2\lambda)(2+\kappa)(1\text{-}\rho) - \left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}\left[2+\kappa-2\lambda(1+\kappa)-\rho(1\text{-}\lambda)(2+\kappa)\right]\right\}$$

$$\frac{\partial z_{12}^*}{\partial t_1} = -\frac{\lambda c\Psi(2F\text{-}t)\left(\frac{\Psi}{\eta}\right)^{-\frac{2}{\lambda}}}{4F\beta(2+\kappa)(1\text{-}\rho)}\left\{\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}\left[2\rho\lambda(1+\kappa)\text{-}\lambda(2+\kappa)+(2+\kappa)(1\text{-}\rho)\right] - \tau c\Psi(1\text{-}2\lambda)(2+\kappa)(1\text{-}\rho)\right\}$$

$$\frac{\partial z_{22}^*}{\partial t_1} = -\frac{\rho\lambda^2 c\kappa\eta(2F-t)\left(\frac{\Psi}{\eta}\right)^{\frac{\lambda-1}{\lambda}}\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{4F\beta(2+\kappa)(1-\rho)\chi} < 0,$$

$$\frac{\partial z_{21}^*}{\partial t_1} = \frac{\lambda^2 c\kappa\eta(2F-t)\left(\frac{\Psi}{\eta}\right)^{\frac{\lambda-1}{\lambda}}\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{4F\beta(2+\kappa)(1-\rho)\chi} > 0.$$

where it can be easily shown that $\frac{\partial z_{12}^*}{\partial t_1} < 0$ for all the exporters $0 \le c \le c_{12} = \left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}/\tau\Psi$.

Accordingly, we define $\hat{c}_z \equiv \frac{(1-\lambda)(2+\kappa)(1-\rho)-\lambda\kappa}{(1-2\lambda)\kappa}\hat{c}_q$ and $\hat{\lambda} \equiv 1 - \frac{\kappa}{2(1+\kappa)-(2+\kappa)\rho}$ and summarize our results as follows:

$$\begin{cases} \text{If } \tau < \hat{\tau} \text{ and } \begin{cases} \lambda < \hat{\lambda}, \text{ then} \frac{\partial z_{11}^*(c)}{\partial t_1} \gtreqless 0 \text{ for} c \lesseqgtr \hat{c}_z \\ \lambda > \hat{\lambda}, \text{ then} \frac{\partial z_{11}^*(c)}{\partial t_1} > 0 \end{cases} \\ \text{If } \tau > \hat{\tau} \text{ and } \begin{cases} \lambda < \hat{\lambda}\ , \text{ then} \frac{\partial z_{11}^*(c)}{\partial t_1} < 0 \\ \lambda > \hat{\lambda}, \text{ then} \frac{\partial z_{11}^*(c)}{\partial t_1} \lesseqgtr 0 \text{ for } c \lesseqgtr \hat{c}_z \end{cases} \end{cases}$$

$$\frac{\partial z_{12}^*(c)}{\partial t_1} < 0,\ \frac{\partial z_{22}^*(c)}{\partial t_1} < 0 \text{ and } \frac{\partial z_{21}^*(c)}{\partial t_1} > 0.$$

By differentiating the illegal emissions $(e_{11}^*, e_{12}^*, e_{22}^*, e_{21}^*)$ with respect to t_1, we have:

$$\begin{aligned} \frac{\partial e_{11}^*}{\partial t_1} &= \frac{\lambda c \Psi \left(\frac{\Psi}{\eta}\right)^{-\frac{2}{\lambda}}}{8F^2(2+\kappa)\beta(\rho-1)} \{c\Psi(2+\kappa)(\rho-1)[2F\chi - (2\lambda-1)t(t-2F)] \\ &\quad + \left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}} \{t(t-2F)[2-2\lambda+\kappa-2\lambda\kappa+(\lambda-1)(2+\kappa)\rho] - 2F(2+\kappa)(\rho-1)\chi\} \Bigg\}, \end{aligned}$$

$$\begin{aligned} \frac{\partial e_{12}^*}{\partial t_1} &= -\frac{\lambda c \Psi \left(\frac{\Psi}{\eta}\right)^{-\frac{2}{\lambda}}}{8F^2(2+\kappa)\beta(\rho-1)} \{\tau c\Psi(2+\kappa)(\rho-1)[(2\lambda-1)(2F-t)t + 2F\chi] \\ &\quad + \left(\frac{\Psi^\kappa \xi}{1+\rho}\right)^{\frac{1}{2+\kappa}} t(t-2F)[2\lambda(1+\kappa)\rho - \lambda(2+\kappa) - (2+\kappa)(\rho-1)] - 2F(2+\kappa)(\rho-1)\chi \Bigg\}, \end{aligned}$$

$$\frac{\partial e_{22}^*}{\partial t_1} = -\frac{\rho\lambda^2 c\kappa t\Psi(2F-t)\left(\frac{\Psi}{\eta}\right)^{-\frac{2}{\lambda}}\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{8F^2(2+\kappa)\beta(1-\rho)} < 0,$$

$$\frac{\partial e_{21}^*}{\partial t_1} = \frac{\lambda^2 c\kappa t\Psi(2F-t)\left(\frac{\Psi}{\eta}\right)^{-\frac{2}{\lambda}}\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{8F^2(2+\kappa)\beta(1-\rho)} > 0.$$

Thus, by defining $\hat{c}_e \equiv \frac{2\lambda[2(1-\rho)+(2-\rho)\kappa](2F-t)+(1-\rho)(2+\kappa)t}{\kappa(8\lambda F+t-4\lambda t)}\hat{c}_q$, we summarize our results as follows:

$$\begin{cases} \frac{\partial e_{11}^*(c)}{\partial t_1} > 0 \quad \text{as} \quad \tau < \hat{\tau}, \\ \frac{\partial e_{11}^*(c)}{\partial t_1} \gtreqless 0 \text{ if } c \lesseqgtr \hat{c}_e \quad \text{as} \quad \tau > \hat{\tau} \end{cases},$$

$$\frac{\partial e_{12}^*(c)}{\partial t_1} \gtreqless 0 \text{ for } c \lesseqgtr \hat{c}_e/\tau,$$

$$\frac{\partial e_{22}^*(c)}{\partial t_1} < 0, \text{ and } \frac{\partial e_{21}^*(c)}{\partial t_1} > 0.$$

Proof of Proposition 7

In addition, we differentiate the aggregate outputs with respect to t_1 and obtain:

$$\frac{\partial Q_1^*}{\partial t_1} = -\frac{\kappa\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{(2+\kappa)\Psi\gamma(1-\rho)} < 0,$$

$$\frac{\partial Q_2^*}{\partial t_1} = \frac{\kappa\rho\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{(2+\kappa)\Psi\gamma(1-\rho)} > 0,$$

$$\frac{\partial Q_w^*}{\partial t_1} = -\frac{\kappa\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}{2\Psi\gamma+\kappa\Psi\gamma} < 0.$$

By focusing on total emissions, we obtain:

$$\frac{\partial Z_1^*}{\partial t_1} = -\frac{\lambda\kappa\xi\eta^{2/\lambda}\Psi^{\kappa-2/\lambda}(2F-t)}{2F\gamma(2+\kappa)^2(1-\rho^2)^2\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1+\kappa}{2+\kappa}}}\left\{\alpha\left\{2(1-\rho)^2\left(1+\rho^{1+\frac{1}{\kappa}}\right)+\lambda\kappa^2\rho(1+\rho)\left(1+\rho^{\frac{1}{\kappa}}\right)\right.\right.$$
$$\left.+\kappa\left\{(1-\rho)^2\left(1+\rho^{1+\frac{1}{\kappa}}\right)-\lambda\left\{1-\rho\left[2+\rho+\rho^{\frac{1}{\kappa}}+\rho^{1+\frac{1}{\kappa}}(2\text{-}\rho)\right]\right\}\right\}\right\}-$$
$$-\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}\left\{2(1-\rho)^2\left(1+\rho^{1+\frac{1}{\kappa}}\right)+\lambda\kappa^2\rho(1+\rho)\left(1+\rho^{\frac{1}{\kappa}}\right)\right.$$
$$\left.\left.+\kappa(1-\rho)\left[1-2\lambda-\rho+\rho^{1+\frac{1}{\kappa}}(1-\rho+2\lambda\rho)\right]\right\}\right\},$$

$$\frac{\partial Z_2^*}{\partial t_1} = \frac{\rho\lambda^2\kappa^2\xi\eta^{2/\lambda}\Psi^{\kappa-2/\lambda}(2F-t)}{2F\gamma(2+\kappa)^2(1-\rho^2)^2\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1+\kappa}{2+\kappa}}}\left\{\alpha\left[\kappa(1+\rho)\left(1+\rho^{\frac{1}{\kappa}}\right)+2\left(\rho+\rho^{\frac{1}{\kappa}}\right)\right]\right.$$
$$\left.+\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}\left[2(1-\rho)\left(1-\rho^{\frac{1}{\kappa}}\right)-\kappa(1+\rho)\left(1+\rho^{\frac{1}{\kappa}}\right)\right]\right\} > 0,$$

$$\frac{\partial Z_w^*}{\partial t_1} = -\frac{\lambda\kappa\xi\eta^{2/\lambda}\Psi^{\kappa-2/\lambda}(2F\text{-}t)\left(1+\rho^{1+\frac{1}{\kappa}}\right)\left\{\alpha(2+\kappa+\lambda\kappa)-\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}\left[2+(1\text{-}2\lambda)\kappa\right]\right\}}{2F\gamma(2+\kappa)^2(1+\rho)^2\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1+\kappa}{2+\kappa}}} < 0.$$

Because $\frac{\partial Z_1^*}{\partial t_1}$ is decreasing in α and $\alpha \geq \left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}$, we have $\frac{\partial Z_1^*}{\partial t_1} < 0$ given that

$$\frac{\left(\frac{\partial Z_1^*}{\partial t_1}\Big|_{\alpha=\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}\right)}{\frac{\lambda\kappa\xi\eta^{2/\lambda}\Psi^{\kappa-2/\lambda}(2F-t)}{2F\gamma(2+\kappa)^2(1-\rho^2)^2\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1+\kappa}{2+\kappa}}}} = -\lambda\kappa\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}(1+\rho^2)\left(1+\rho^{1+\frac{1}{\kappa}}\right) < 0.$$

Given that $\alpha \geq \left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}$, it is obvious that $\frac{\partial Z_2^*}{\partial t_1} > 0$. Moreover, because $\frac{\partial Z_w^*}{\partial t_1}$ is decreasing in α and $\alpha \geq \left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}$, we have $\frac{\partial Z_w^*}{\partial t_1} < 0$ given that

$$\frac{\left(\frac{\partial Z_w^*}{\partial t_1}\Big|_{\alpha=\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}}\right)}{\frac{\lambda\kappa\xi\eta^{2/\lambda}\Psi^{\kappa-2/\lambda}(2F\text{-}t)\left(1+\rho^{1+\frac{1}{\kappa}}\right)}{2F\gamma(2+\kappa)^2(1+\rho)^2\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1+\kappa}{2+\kappa}}}} = -\frac{(1-\rho)^2\left(\frac{\Psi^\kappa\xi}{1+\rho}\right)^{\frac{1}{2+\kappa}}\left(1+\rho^{1+\frac{1}{\kappa}}\right)}{\rho} < 0.$$