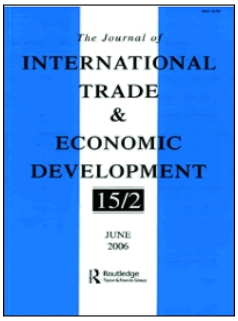

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Induced clean technology adoption and international trade with heterogeneous firms

Jingbo Cui

School of Economics and Management, Wuhan University, Wuhan, China

ABSTRACT

This paper introduces an environmental externality and factor-biased technology adoption into a trade model with heterogeneous firms. This study explores how firms' decisions of technology adoption and of exports are affected by openness to trade and the stringency of environmental regulations. It shows that: (1) these decisions induced by tightened environmental policies depend upon whether the upgraded technology is labor-biased or emission-biased; (2) the environmental impact of trade cost reductions on the aggregate emissions and price of emissions permits varies with the factor-biased feature; and (3) regardless of the factor-biased feature, the trade cost reduction induces firms to export and to upgrade the factor-biased technology, while it forces the least productive firms to exit the market. Moreover, the model is further calibrated to simulate policy scenarios of bilateral and unilateral variations in trade variable costs and environmental policies. The bilateral reduction of emissions cap may contribute to welfare gains in both home and foreign countries. The unilateral action of tightening environmental policy in the home country may hurt the home country, but makes the foreign country better off.

KEYWORDS Technology adoption; factor-biased technical change; cap-and-trade; heterogeneous firms

JEL CLASSIFICATION F18, Q55, Q56

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1. Introduction

Environmental economists have been long engaged in debates about the environmental effect of international trade and the economic consequences of environmental policies. These debates have been recently fueled by trade liberalization and climate change; both are among the most pressing interrelated policy challenges facing the world today. Due to significant contributions to both values of exports and air emissions, manufacturer behaviors in response to trade and climate policies have gradually taken center stage in the debate.[1] As suggested from empirical evidence by Levinson (2009, 2014), technology improvements in the manufacturing sector have been found to play a key role in cleaning the environment.[2] While the growing literature focuses on the effectiveness of environmental policy on technology adoption,[3] until recently, the role of firms' heterogeneous

CONTACT Jingbo Cui jbcui@whu.edu.cn

productivity in the response of technology adoption to environmental policy has received little attention. Substantial evidences have been documented the existence of productivity variations among manufacturing firms (Bernard et al. 2003; Tybout 2003). In polluting manufacturing sectors, a recent empirical work by Greenstone et al. (2012) provides further corroborating evidence suggesting that heterogeneous productivity plays an important role in determining firms' entry and exit in response to environmental regulations. Understanding heterogeneous manufactures' endogenous decisions for clean technology adoption and entry/exit is important for any assessment of future trade negotiations and climate policy coordinations.

This paper seeks to examine the interacted effects of environmental policies and the openness to trade on the intra-industry firm dynamics, industry composition, and mass of firms. The model accounts for both the firm-level heterogeneous productivity and their decisions for technology adoption and of entry/exit. With this objective, this study incorporates an exogenous binary technology choice and pollution into the Melitz-type trade model with heterogeneous firms (Melitz 2003). Production uses a non-polluting input (i.e. labor) as a primary input and emits pollution, which is regarded as another input of the production in a manner analogous to Copeland and Taylor (1994). Technology adoption is modeled as a choice between the *low* and *high* technologies, assuming the latter is a factor-augmenting technical change relative to the former. Whereas adopting the *high* technology requires payment for more fixed production costs, it has a lower marginal cost relative to the *low* technology. To further improve and extend the model, this paper considers the direction of technical changes as in Acemoglu (2002). The technical change could be biased toward either the clean labor resource or the polluting emissions resource. I refer to the former as the clean technological improvement, while interpret the latter as the dirty technological improvement. Unlike the literature that investigates the endogenous directed technical change in response to environmental instruments (Acemoglu et al. 2012; Grimaud and Rouge 2008), this paper focuses on how policy instruments affect firms' decisions of technology choices and entry–exit given the direction of the exogenous technical change.

In the theoretical model, this paper considers bilateral variations in trade variable costs and environmental instruments, and conduct comparative statics on these variations. The analytical results are the following: (1) the induced effects of stringent environmental controls on firms' decisions of technology choice and of entry–exit depend upon whether the upgraded *high* technology is labor-biased or emission-biased; (2) whereas the aggregate emissions are fixed at the cap level, the environmental impact of the trade cost reduction is captured by its indirect effect on the price of emissions permits, varying with the factor-biased feature; (3) although the response of the relative emissions price to trade varies with the direction of technical change, the effects of exposure to trade on the intra-industry firm dynamics hinge on the relative strength between a positive effect on the selection to trade and a negative effect on technology adoption; and (4) regardless of the factor-biased technical change, the selection to trade effect dominates the technology adoption effect, the trade cost cut induces firms to export and upgrade the factor-biased technology, but drops the least productive firms from the domestic market.

By a stylized, yet, conventional calibration of the model, numerical results regarding the intra-industry effects of a bilateral reduction in the trade variable cost and of a coordinated stringent environmental policy are consistent with the theoretical predictions of the model. Moreover, a non-coordinated unilateral stringent environmental policy is simulated, and its welfare implications in home and foreign countries are examined. The unilateral action of tightening the environmental policy in the home country may cause the home country to suffer substantial welfare losses mainly from the declining mass of consumption varieties. This unilateral policy, however, has a welfare-enhancing implication on the foreign country.

This paper is related to at least three important strands of literature. The first deals with trade and the environment. A large body of literature built upon Copeland and Taylor (1994, 1995) theoretically and empirically examines the environmental consequence of trade at the aggregate level (e.g. industry, country) (Antweiler, Copeland, and Taylor 2001; Frankel and Rose 2005; Levinson and Taylor 2008; Managi, Hibiki, and Tsurumi 2009; McAusland and Millimet 2013). As the trade community reaches a consensus on the firm-level heterogeneity in productivity, recent related work has started redirecting attention on firms' differences in productivity. Using plant-level panel data from various countries, some empirical studies have found ample evidence supporting the existence of heterogeneous productivity among polluting firms and positive correlations among productivity, export status, and environmental performance (Galdeano-Gomez 2010; Girma and Hanley 2015; Cui et al. 2016; Cao et al. 2016; Holladay 2016).[4] Such fruitful corroborating evidence calls for a need to model the firm-level heterogeneous productivity when it comes to examining the effects of environmental regulations.

Second, this paper adds to the growing literature that seeks to extend the Melitz model to examine the environmental effects of trade (Erdogan 2014; Kreickemeier and Richter 2014) and the economic implications of environmental policies (Konishi and Tarui 2015; Yokoo 2009). Kreickemeier and Richter (2014) decompose the environmental impact of trade liberalization into the scale effect and reallocation effect. They show the positive effect of exposure to trade on aggregate emissions, if emissions intensity decreases strongly with firm productivity. Erdogan (2014) introduces an environmental policy and factor en-dowment into a multi-country general equilibrium model, based upon the Melitz framework. Environmental pollution is incorporated in a Copeland–Taylor's manner, which treats pollution as an alternative input of the production. The calibrated model is used to quantify the environmental consequences of free trade and the economic impacts of environmental harmonization regulations. Yokoo (2009) develops a simple Melitz framework with environmental pollution in the Copeland–Taylor's manner to investigate the so-called Porter hypothesis. Another related paper by Konishi and Tarui (2015) also uses the Copeland–Taylor's technique in modeling pollution. They examine the effects of emissions trading designs on the equilibrium mass of firms, entry–exits, and social welfare. The main focus of their work is on comparing and contrasting the long-run implications of alternative emission allocation rules (e.g. quantity-based, grandfathering schemes, etc.). Following the Copeland–Taylor's technique, which allows to derive highly tractable analytical results, this paper assumes the stringency of environmental controls in a form of a reduction in emissions cap and aims to highlight the long-run effects of the stringent environmental policy on technology adoption.

Another related work by Forslid et al. (2014) extends the Melitz model by allowing heterogeneous firms to emit pollution and to make a continuous investment in abating pollution. They assume a Hicks-neutral production technology, suggesting the better technology is always cleaner,[5] whereas this paper considers the factor-biased technology adoption between two discrete technology choices, allowing the upgraded choice to be either dirty or clean. Such an extension is particularly important when it comes to assessing the economic impacts of stringent environmental policies. The present paper shows that the impacts of strict environmental controls on firms' decisions of technology adoption vary with the factor-biased feature of technical change. In addition, Forslid et al. (2014) focus on the effects of trade liberalization, while this paper examines the impacts of both trade cost reductions and stringent environmental policies.

Third, this paper also complements a line of studies that incorporate technology adoption in the Melitz framework. Bustos (2011b) theoretically and empirically investigates the effects of trade liberalization on technology adoption, using panel data from the Argentinean manufacturing firms. Unel (2013)'s attention is on the welfare implication of a unilateral reduction in the technology adoption cost. In these two studies, technology is characterized by a single labor input. Another two recent studies incorporate a skill-biased technology choice into the Melitz framework. Bustos (2011a) considers a simple Cobb–Douglas (CD) production function, while Bas (2012) assumes a constant elasticity of substitution (CES) structure on the technology. Using the convenient feature of the CD function, Bustos (2011a) shows the impact of exports on skill upgrading and finds the supporting evidence from Argentinean industrial firms. Bas (2012) lays out a theoretical model to motivate the empirical investigation regarding the effects of exports on skill upgrading, using the Chilean manufacturing plant-level data. Along this line, this paper extends their model set-up by linking the impacts of trade liberalization on technology upgrading and skill premium with the direction of the factor-biased technical change.

The remainder of this paper proceeds as follows. The next section introduces the model and characterizes the equilibrium in an open economy with costly trade. Section 3 examines the effects of the tightened environmental policies, while Section 4 investigates the effects of trade liberalization. Section 5 presents the numerical simulations on bilateral and unilateral variations in policy instruments of interests. The final section concludes this paper.

2. The model

The model assumes a world of two symmetric countries (i.e. home and foreign), each with a representative consumer. An asterisk ($*$) is used to denote foreign country variables to distinguish them from home country variables when necessary. The equilibrium conditions for the foreign country are omitted, but can be derived analogously.

2.1. *Preference*

The representative consumer has a CES preference defined over a continuum of domestic and imported varieties. This consumer also suffers the disutility of pollution arising from the production process. The per-period utility function is

$$U = \left[\int_{\omega \in \{\Omega, \Omega^*\}} q(\omega)^{\rho} d\omega \right]^{1/\rho} - D(E, E^*), \ \rho \in (0, 1) \tag{1}$$

where (E, E^*) denote aggregate emissions in home and foreign countries, respectively. Ω governs the set of varieties. Varieties indexed by ω are substituted with a constant elasticity of $\sigma \equiv 1/(1-\rho) > 1$. In the utility function (1), $D(\cdot)$ is the domestic damage function. As suggested in Kreickemeier and Richter (2014), $D(\cdot)$ could take a simple form of $D(E, E^*) = \theta(E + E^*)$ when it comes to the numerical simulation. θ refers to social marginal cost of a particular global pollution (e.g. CO_2).

As a result of the Dixit–Stiglitz monopolistic competition (Dixit and Stiglitz 1977), for any varieties produced in the home country, the residual demand in the domestic market, denoted by $q_{\omega d}$, and that in the export market, denoted by $q_{\omega x}$, have the iso-elastic forms:

$$q_{\omega d} = \frac{RP^{\sigma-1}}{(p_{\omega d})^{\sigma}}; \quad q_{\omega x} = \frac{R^*(P^*)^{\sigma-1}}{(p_{\omega x})^{\sigma}} \tag{2}$$

where d and x represent the domestic and export markets, respectively. $(p_{\omega d}, p_{\omega x})$ denote individual variety prices in the domestic and export markets, respectively. (R, R^*) are the aggregate expenditure indices. (P, P^*) are the aggregate prices. The price index dual to the utility function (1) is given by $P^{1-\sigma} = \int_{\omega\in\{\Omega,\Omega^*\}} p(\omega)^{1-\sigma}\, d\omega$.

2.2. Production

The timing of events follows the standard Melitz model, except for adding technology choices prior to production. In the beginning of each period, there is a large pool of identical firms prior to entry. To enter the market, each firm pays a time-invariant entrance fee of $f_e > 0$ as the initial investment. The new entrant then draws the firm-specific productivity φ from a common Pareto distribution, $G(\varphi) = 1 - \varphi^{-c}$, with a positive support of $(0, \infty)$, where $c > \sigma - 1$.[6] Upon observing the draw, the firm decides whether to exit immediately. If the firm chooses to produce, it could adopt technology $j \in \{l, h\}$ to operate a plant with fixed production costs of $f_j > 0$. In addition, the firm could export with fixed costs of $f_x > 0$ and iceberg transportation costs of $\tau > 1$. At the end of the period, the firm faces a constant probability, $\delta \in (0, 1)$, of an idiosyncratic shock that forces it to exit regardless of its technology choice. Following Bas (2012) and Bustos (2011a), all fixed costs (i.e. f_e, f_j, and f_x) are measured by the aggregate output Q, which is a numeraire good.

Each firm with firm-specific productivity φ produces a differentiated variety. Production requires labor inelastically supplied at the endowment level of $\overline{L}$, and emits pollution as by-products. Following Copeland and Taylor (1994)'s technique for treating pollution as an additional factor of production, the production function for a firm with productivity φ and technology j is assumed to have the following CES form:

$$q_j = \varphi \left[(\beta_j e)^{\frac{\eta-1}{\eta}} + (\alpha_j l)^{\frac{\eta-1}{\eta}} \right]^{\eta/(\eta-1)} \tag{3}$$

where l is the variable labor input, e denotes pollution emissions, β_j and α_j are two separate technology terms, and $\eta \in (0, \infty)$ governs the elasticity of substitution between the two factors. Assumptions about parameters (β_j, α_j) in the production function are imposed in the subsection of technology adoption.

To model the underlying incentive for all firms to consider and possibly adopt ‘ greener’ technologies, each firm must purchase emission permits from the domestic government to emit the equivalent amounts of pollution. Given the wage rate w and the permit price p_e, the variable cost function dual to the production technology (3) is

$$C_j(\varphi, w, p_e) = \frac{q_j c_j(w, p_e)}{\varphi} = \frac{q_j}{\varphi} \left[\left(\frac{p_e}{\beta_j}\right)^{1-\eta} + \left(\frac{w}{\alpha_j}\right)^{1-\eta} \right]^{1/(1-\eta)} \tag{4}$$

Hence, $c_j(w, p_e)/\varphi$ is the marginal cost of production via technology j.

Each firm with firm-specific productivity φ faces domestic and export residual demand curves with a constant elasticity of $\sigma > 1$ defined in equation (2). Exporting requires fixed costs of $f_x > 0$, thereafter sunk. It is also subject to the standard iceberg form of variable costs (e.g. transportation costs), whereby $\tau > 1$ units of a good must be shipped for one unit to arrive at the destination. Under CES preferences, the profit maximizing price is a constant markup over marginal costs. Firms charge a higher price in the export market than the domestic market because of trade variable costs. The optimal pricing rules and output levels across markets for firms adopting technology j are given by

$$p_{jd}(\varphi) = \frac{c_j}{\rho\varphi}; \quad p_{jx}(\varphi) = \frac{\tau c_j}{\rho\varphi} \tag{5}$$

$$q_{jd}(\varphi) = RP^{\sigma-1}\left(\frac{\rho\varphi}{c_j}\right)^{\sigma}; \quad q_{jx}(\varphi) = R^*(P^*)^{\sigma-1}\left(\frac{\rho\varphi}{\tau c_j}\right)^{\sigma} \tag{6}$$

Note that $c_j \equiv c_j(p_e, w)$ is a function of endogenous input prices. Revenues earned from the domestic and export markets follow as

$$r_{jd}(\varphi) = RP^{\sigma-1}\left(\frac{\rho\varphi}{c_j}\right)^{\sigma-1}; r_{jx}(\varphi) = R^*(P^*)^{\sigma-1}\left(\frac{\rho\varphi}{\tau c_j}\right)^{\sigma-1} \tag{7}$$

Using Shephard's lemma, firm's variable labor and emissions permit input demands are

$$l_{jd}(\varphi) = \frac{\rho s_j^l}{w} r_{jd}(\varphi); \quad l_{jx}(\varphi) = \frac{\rho s_j^l}{w} r_{jx}(\varphi) \tag{8}$$

$$e_{jd}(\varphi) = \frac{\rho s_j^e}{p_e} r_{jd}(\varphi); \quad e_{jx}(\varphi) = \frac{\rho s_j^e}{p_e} r_{jx}(\varphi) \tag{9}$$

where $s_j^e \equiv \frac{\partial c_j}{\partial p_e}\frac{p_e}{c_j}$ and $s_j^l \equiv \frac{\partial c_j}{\partial w}\frac{w}{c_j}$ refer to the cost share for emissions permits and labor, respectively. By the cost function's property, $s_j^e + s_j^l = 1$.

Each firm's profits are separated into components from its domestic and export sales. The fixed production cost and fixed export cost are apportioned to the domestic profit, $\pi_{jd}(\varphi)$, and to the export profit, $\pi_{jx}(\varphi)$, respectively. The profit earned from each market is

$$\pi_{jd}(\varphi) = \frac{R}{\sigma}\left(\frac{P\rho}{c_j}\right)^{\sigma-1}\varphi^{\sigma-1} - Pf_j; \quad \pi_{jx}(\varphi) = \frac{R^*}{\sigma}\left(\frac{P^*\rho}{\tau c_j}\right)^{\sigma-1}\varphi^{\sigma-1} - Pf_x \tag{10}$$

where f_j denotes the fixed production of adopting technology j.

2.3. Technology adoption

Technology adoption is modeled as a choice between two different technologies – the *low* and the *high* technology, assuming the latter is a factor-augmenting technical change relative to the former. These two technologies differ in: (1) the fixed production cost of adopting technology denoted by $f_j > 0$, thereafter sunk, where $j \in \{l, h\}$ (l refers to the *low* technology and h the *high* technology); and (2) the technology-specific marginal cost.

Assumption 2.1: $f_h > f_l$, $c_h(w, p_e) < c_l(w, p_e)$, $\forall\, w, p_e > 0$.

The former term, $f_h > f_l$, implies that adopting the *high* technology requires higher fixed costs than adopting the *low* technology. Thus, define $f \equiv f_h - f_l > 0$ as extra fixed costs for upgrading technology. The latter term, $c_h(w, p_e) < c_l(w, p_e)$, captures that the *high* technology has lower marginal costs relative to the *low* technology due to the factor-augmenting feature of technical change.

The model further considers the direction of technical change as in Acemoglu (2002). The technology terms (β_j, α_j) and the elasticity of substitution η in the CES production function (3) are assumed such that the technical change is factor-biased.[7] When the *high* technology is labor-biased, the *high* technology is cleaner than the *low* technology. On the contrary, when the *high* technology is emission-biased, it is actually dirtier than the alternative. In response to the rising emission price, the cost-saving advantage of adopting the *high* technology, captured by the relative marginal costs c_l/c_h, varies with the direction of technical change.

Lemma 2.1: *Given Assumption 2.1 about the factor-biased technology adoption*

(i) if the high technology is labor-biased (hence clean), then the cost-saving advantage for adopting the high technology rises with the relative permit price, that is, $\frac{\partial(c_l/c_h)}{\partial(p_e/w)} > 0$;
(ii) if the high technology is emission-biased (hence dirty), then the cost-saving advantage for adopting the high technology falls with the relative permit price, that is, $\frac{\partial(c_l/c_h)}{\partial(p_e/w)} < 0$;
(iii) if the high technology is Hicks-neutral, then the cost-saving advantage for adopting the high technology is invariant with the relative permit price, that is, $\frac{\partial(c_l/c_h)}{\partial(p_e/w)} = 0$.

Proof: See Appendix. ■

When the *high* technology is labor-biased, it requires more labor than emission permits in cost shares, that is, $s_h^l > s_l^l$ (or equivalently $s_h^e < s_l^e$). As the emission permit price rises relative to wage rate, the labor-biased *high* technology requires employment of more cheap labor rather than expensive permits, thereby raising the relative marginal costs, so $\partial(c_l/c_h)/\partial(p_e/w) > 0$. Thus, the gain for adopting the *high* technology becomes more prominent as the permit price rises. The feature suggests that the economy would be favorable for adopting the labor-biased *high* technology in response to environmental pressures. On the contrary, when the *high* technology is emission-biased ($s_h^e > s_l^e$), it now requires to purchase more expensive emissions permits than cheap labor. As a consequence, the gain for adopting the *high* technology falls as the environmental burden rises, thus $\partial(c_l/c_h)/\partial(p_e/w) < 0$. The economy is not conducive to the emission-biased *high* technology adoption. If Hicks-neutral technical change occurs ($s_h^e = s_l^e$), the incentive for upgrading to the *high* technology becomes invariant to the relative permit price, $\partial(c_l/c_h)/\partial(p_e/w) = 0$. The relationship between the relative marginal cost and permit price does not rely on the specific production function form, but whether the direction of technical change is biased towards labor or emissions. This relationship plays a key role in discussing policy variations in what follows.

2.4. Entry and exit

There exist three productivity cut-offs: (1) the zero-profit productivity cut-off for adopting the *low* technology, denoted by φ_l, above which firms decide to enter the market and adopt the *low* technology; (2) the zero-profit productivity cut-off for exporting, denoted by φ_x, above which firms select to export; and (3) the equivalent-profit productivity cut-off for adopting the *high* technology over the alternative, denoted by φ_h, above which firms adopt the *high* technology. These cut-offs are defined as follows:

$$\pi_{ld}(\varphi_l) = \frac{R}{\sigma}\left(\frac{P\rho}{c_l}\right)^{\sigma-1}(\varphi_l)^{\sigma-1} - Pf_l = 0 \tag{11a}$$

$$\pi_{lx}(\varphi_x) = \frac{R^*}{\sigma}\left(\frac{P^*\rho}{\tau c_l}\right)^{\sigma-1}(\varphi_x)^{\sigma-1} - Pf_x = 0 \tag{11b}$$

$$\begin{aligned}&\pi_{hd}(\varphi_h) + \pi_{hx}(\varphi_h) - \pi_{ld}(\varphi_h) - \pi_{lx}(\varphi_h)\\ &= \left(1+\tau^{1-\sigma}\Lambda\right)\left[\left(\frac{c_l}{c_h}\right)^{\sigma-1} - 1\right]\frac{R}{\sigma}\left(\frac{P\rho}{c_l}\right)^{\sigma-1}(\varphi_h)^{\sigma-1} - Pf = 0\end{aligned} \tag{11c}$$

where $f \equiv f_h - f_l > 0$ represents extra fixed costs for upgrading technology. $\Lambda \equiv R^*(P^*)^{\sigma-1}/(RP^{\sigma-1})$ denotes the relative foreign market potential, the ratio for foreign market potential to home market potential as defined in Okubo (2009). If countries are identical, the relative foreign market potential $\Lambda = 1$.

A continuum of heterogeneous firms is partitioned by technology choice and market status. With a specific cost structure, one could guarantee that all *high* technology firms serve both domestic and export markets, while only a fraction of the *low* technology firms export, as stated in the following lemma.[8]

Assumption 2.2: The cost structure satisfies

$$\Lambda\tau^{1-\sigma} f_l < f_x < f\left(1+\Lambda^{-1}\tau^{\sigma-1}\right)^{-1}\left[\left(\frac{c_l}{c_h}\right)^{\sigma-1} - 1\right]^{-1}$$

where $\Lambda \equiv R^*(P^*)^{\sigma-1}/(RP^{\sigma-1})$.

Lemma 2.2: *Given Assumption 2.2, all high technology firms serve both domestic and export markets, while only a fraction of the low technology firms export, that is,* $\varphi_l < \varphi_x < \varphi_h$.

The effects of trade cost reductions and stringent environmental regulations on the intra-industry firm decisions are captured by variations in the relative productivity cut-offs. Using the definition for productivity cut-offs in equations (11a) and (11c), there are three ways to express the relative equilibrium cut-offs that vary with policy instruments and trade costs. First, consider firms adopting the *low* technology, but serving different markets:

$$\left(\frac{\varphi_l}{\varphi_x}\right)^{\sigma-1} = \frac{\Lambda}{\tau^{\sigma-1}}\frac{f_l}{f_x} \tag{12}$$

The productivity gap, φ_l/φ_x, captures the proportion of exporters conditional on successful entry. It follows immediately that a lower trade cost (either τ or f_x) increases profits from overseas; hence, that raises the proportion of exporters. A rise in the fixed costs for adopting the *low* technology f_l makes the least productive firms difficult to survive in the market, thereby raising the fraction of exporters. If countries are not identical, the productivity gap also depends upon the relative strength of the home and foreign market potential, denoted by $RP^{\sigma-1}$ and $R^*(P^*)^{\sigma-1}$, respectively. Such relative strength also reflects the relative market size across countries. The smaller the relative foreign market potential Λ, the less promising for selling products overseas will be.

The second comparison worthy of attention involves the equilibrium relationship between technology adoption cut-offs:

$$\left(\frac{\varphi_l}{\varphi_h}\right)^{\sigma-1} = (1+\tau^{1-\sigma}\Lambda)\left[\left(\frac{c_l}{c_h}\right)^{\sigma-1} - 1\right]\frac{f_l}{f} \tag{13}$$

The gap between the least productive *low* technology firms and the least productive *high* technology firms, captured by φ_l/φ_h, reflects the fraction of firms adopting the *high* technology. This fraction decreases in the variable trade cost τ, but increases in the relative marginal costs c_l/c_h. If a reduction in the variable trade cost reduces the permit price, there exists an indirectly negative impact on the relative marginal costs, leading to an ambiguous effect on the relative productivity cut-off φ_l/φ_h.

Equations (12) and (13) together give rise to those that serve both the domestic and export markets, but adopt different technologies:

$$\left(\frac{\varphi_h}{\varphi_x}\right)^{\sigma-1} = \left(\frac{1}{1+\tau^{\sigma-1}\Lambda^{-1}}\right)\left[\left(\frac{c_l}{c_h}\right)^{\sigma-1} - 1\right]^{-1}\frac{f}{f_x} \tag{14}$$

This expression shows that the proportion of the *low* technology firms serving both the domestic and export markets, represented by φ_h/φ_x, is inversely related to trade costs (both variable and fixed costs), relative marginal costs c_l/c_h, and the relative home market potential index Λ^{-1}. Changes like a reduction in the trade costs or a rise in the relative foreign market size are favorable for exporting decisions; hence, they raise the productivity cut-off gap φ_h/φ_x. However, an increase in the relative marginal costs c_l/c_h encourages firms to adopt the *high* technology, thereby shortening the cut-off gap.

Given an unbounded pool of potential new entrants in any equilibrium with unrestricted entry, the expected value for entry must equal its sunk cost f_e. Thus, the free entry condition is $\bar{\pi}\,[1-G(\varphi_l)] = \delta P f_e$, where $\bar{\pi}$ denotes the expected profit from successful entry. Following the technique provided in Bernard, Redding, and Schott (2007), the free entry condition under costly trade could be rewritten as follows:

$$f_l\int_{\varphi_l}^{\infty}\left[\left(\frac{\varphi}{\varphi_l}\right)^{\sigma-1} - 1\right]\mu(\varphi)d\varphi + f_x\int_{\varphi_x}^{\infty}\left[\left(\frac{\varphi}{\varphi_x}\right)^{\sigma-1} - 1\right]\mu(\varphi)d\varphi$$
$$+ f\int_{\varphi_h}^{\infty}\left[\left(\frac{\varphi}{\varphi_h}\right)^{\sigma-1} - 1\right]\mu(\varphi)d\varphi = \frac{\delta f_e}{1-G(\varphi_l)} \tag{15}$$

where $\mu(\varphi)$ is the conditional distribution of $g(\varphi)$ on $[\varphi_l, \infty]$, that is, $\mu(\varphi) = g(\varphi)/[1 - G(\varphi_l)]$ if $\varphi \geq \varphi_l$.

In the end, the law of motion implies that the mass of potential entrants M_e, who enter successfully, exactly replace the mass of incumbents M, who are hit by the bad shock and exit, that is, $\delta M = [1 - G(\varphi_l)]M_e$. The aggregate mass of the *low* technology firms M_l, of exporting firms M_x, and of the *high* technology firms M_h, are given by $M_l = \lambda_l M$, $M_x = \lambda_x M$, and $M_h = \lambda_h M$, respectively. λ_l, λ_x, and λ_h denote the *ex post* fraction of the *low* technology firms, of exporters, and of the *high* technology firms, respectively. Given the Pareto productivity distribution and the equilibrium related cut-offs in equations (12)–(14), the *ex post* fractions associated with the relative equilibrium cut-off values are

$$\lambda_l \equiv \frac{G(\varphi_h) - G(\varphi_l)}{1 - G(\varphi_l)} = 1 - \left(\frac{\varphi_l}{\varphi_h}\right)^c; \lambda_x \equiv \frac{1 - G(\varphi_x)}{1 - G(\varphi_l)} = \left(\frac{\varphi_l}{\varphi_x}\right)^c;$$
$$\lambda_h \equiv 1 - \lambda_l = \left(\frac{\varphi_l}{\varphi_h}\right)^c \tag{16}$$

2.5. Aggregate variables

Under the equilibrium pricing rule, the aggregate price index includes individual prices of domestic and imported varieties, both produced with either the *low* or *high* technologies:

$$P^{1-\sigma} = \int_{\varphi_l}^{\varphi_h} p_{ld}^{1-\sigma}(\varphi)M\mu(\varphi)d\varphi + \int_{\varphi_h}^{\infty} p_{hd}^{1-\sigma}(\varphi)M\mu(\varphi)d\varphi$$
$$+ \int_{\varphi_x^*}^{\varphi_h^*} p_{lx}^{*1-\sigma}(\varphi)M^*\mu^*(\varphi)d\varphi + \int_{\varphi_h^*}^{\infty} p_{hx}^{*1-\sigma}(\varphi)M^*\mu^*(\varphi)d\varphi \tag{17}$$

The aggregate revenue equals the sum of expenditure spent on domestic and imported varieties:

$$R = \int_{\varphi_l}^{\varphi_h} r_{ld}(\varphi)M\mu(\varphi)d\varphi + \int_{\varphi_h}^{\infty} r_{hd}(\varphi)M\mu(\varphi)d\varphi + \int_{\varphi_x^*}^{\varphi_h^*} r_{lx}^*(\varphi)M^*\mu^*(\varphi)d\varphi$$
$$+ \int_{\varphi_h^*}^{\infty} r_{hx}^*(\varphi)M^*\mu^*(\varphi)d\varphi$$
$$= \int_{\varphi_l}^{\varphi_h} r_{ld}(\varphi)M\mu(\varphi)d\varphi + \int_{\varphi_x}^{\varphi_h} r_{lx}(\varphi)M\mu(\varphi)d\varphi + \int_{\varphi_h}^{\infty} [r_{hd}(\varphi) + r_{hx}(\varphi)]M\mu(\varphi)d\varphi \tag{18}$$

The second equality follows from the balanced trade condition where the home country's aggregate imports from the foreign should equal its aggregate exports.

The equilibrium mass of firms is given by

$$M = \frac{R}{\bar{r}} \tag{19}$$

where the average revenue $\bar{r} = \int_{\varphi_l}^{\varphi_h} r_{ld}(\varphi)\mu(\varphi)d\varphi + \int_{\varphi_x}^{\varphi_h} r_{lx}(\varphi)\mu(\varphi)d\varphi + \int_{\varphi_h}^{\infty}[r_{hd}(\varphi) + r_{hx}(\varphi)]\mu(\varphi)d\varphi$.

The aggregate income, $w\bar{L} + p_e\bar{E}$, collected from the total labor payment and emissions permit rent, is redistributed to the representative consumer in a lump-sum fashion. In equilibrium, the aggregate income equals aggregate revenue spent on both domestic and imported varieties, and the expected expenditure on fixed costs expressed in the square bracket. Thus, $w\overline{L} + p_e\overline{E} = R + \left[\delta P f_e/(1 - G(\varphi_d)) + P f_l + \lambda_x P f_x + \lambda_h P f\right]$.

With an inelastic supply of labor $\overline{L}$ and a fixed cap of emissions permits $\overline{E}$, the factor market clearing conditions are:

$$\overline{L} = L \equiv M\left\{\int_{\varphi_l}^{\varphi_h} l_{ld}(\varphi)\mu(\varphi)d\varphi + \int_{\varphi_x}^{\varphi_h} l_{lx}(\varphi)\mu(\varphi)d\varphi + \int_{\varphi_h}^{\infty} \left[l_{hd}(\varphi) + l_{hx}(\varphi)\right]\mu(\varphi)d\varphi\right\} \quad (20)$$

$$\overline{E} = E \equiv M\left\{\int_{\varphi_l}^{\varphi_h} e_{ld}(\varphi)\mu(\varphi)d\varphi + \int_{\varphi_x}^{\varphi_h} e_{lx}(\varphi)\mu(\varphi)d\varphi + \int_{\varphi_h}^{\infty} \left[e_{hd}(\varphi) + e_{hx}(\varphi)\right]\mu(\varphi)d\varphi\right\} \quad (21)$$

The aggregate emissions on the right-hand side of equation (21) are decomposed into two parts: the mass of active firms and the composition of industry with trade and technique effects. This intra-industry composition consists of three emissions contributors: (1) *low*-tech firms, which produce domestic varieties; (2) *low*-tech firms, which export; and (3) *high*-tech firms, which produce both domestic and exported varieties.

With the Pareto-distributed firm-level productivity together with the relative equilibrium cut-offs in equation (16), the aggregate demand of emissions could be rewritten as follows:

$$E = M\frac{c\sigma s_l^e P f_l}{\gamma p_e}\left\{1 + \Lambda\tau^{1-\sigma}\lambda_x^{\gamma/c} + (1 + \Lambda\tau^{1-\sigma})\left[\frac{s_h^e}{s_l^e}\left(\frac{c_l}{c_h}\right)^{\sigma-1} - 1\right]\lambda_h^{\gamma/c}\right\} \quad (22)$$

where $\gamma \equiv c - \sigma + 1 > 0$. If countries are not identical, the relative foreign market potential $\Lambda \neq 1$. Thus, the larger the foreign market size is, the higher the aggregate demand of emissions in the home country would be, due to the expansion of overseas market. In addition, the expression in the curly bracket in equation (22) indicates the weighted average productivity index with the mass of both exporters and technology upgrading firms accounted for.

2.6. Equilibrium

The stationary equilibrium of the costly trade economy with the emissions permit cap-and-trade scheme is a vector of six unknowns, $\{\varphi_l, \varphi_x, \varphi_h, w, p_e, M\}$, subject to six equations in each country (home and foreign): two equilibrium relationships between productivity cut-offs (12) and (13) (any two conditions could derive the third one), the free entry condition (15), the equilibrium mass of firms (19), the labor market clearing condition (20), and the emissions permit market clearing condition (21).

Using equations (20) and(21) and the CES technology structure, the relative aggregate demand for emissions to labor is derived as follows (please refer to the Appendix for the derivation):

$$\left(\frac{E}{L}\right)^D = \frac{ws_l^e}{p_e s_l^l}\left\{1+\left(\frac{s_h^e}{s_l^e}-\frac{s_h^l}{s_l^l}\right)\frac{s_l^l}{s_h^l}\left[1+\frac{s_l^l}{s_h^l}A\right]^{-1}\right\}$$

$$= \left(\frac{w}{p_e}\right)^{\eta}\left(\frac{\beta_l}{\alpha_l}\right)^{\eta-1}\left\{1+\left[\left(\frac{\beta_l\alpha_h}{\beta_h\alpha_l}\right)^{1-\eta}-1\right]\left[1+\left(\frac{\alpha_l c_l}{\alpha_h c_h}\right)^{\eta-1}A\right]^{-1}\right\}$$

where $A \equiv (\frac{\lambda_x f_x}{\lambda_h f}+\frac{f_l}{\lambda_h f})[1-(\frac{c_l}{c_h})^{1-\sigma}]-(\frac{c_l}{c_h})^{1-\sigma}$.

Proposition 2.1: *The relative aggregate demand of emissions to labor decreases in the emissions permit price relative to wage rate, that is,* $\partial(\frac{E}{L})/\partial(\frac{p_e}{w}) < 0$, *if* $\sigma \geq \eta$.

Proof: See Appendix. ∎

The relative aggregate demand for emissions to labor falls, as the relative permit price to wage rate rises, if the elasticity of substitution among varieties of consumption is greater than the elasticity of substitution between factors of production, that is, $\sigma \geq \eta$.[9] This result holds true regardless of whether technical change is labor-biased or emission-biased. The inelastic factor supply ($\overline{E}$ & $\overline{L}$) and the downward-sloping relative aggregate demand together could deduce the equilibrium permit price relative to the wage rate.

3. Stringent environmental policy

The current model is well suited to investigate mechanisms that exposure to trade and environmental policy come into play and interact. To make the derivation tractable, consider changes of policy instruments in a bilateral and symmetric way. This paper maintains the assumption that the firms' partitioning pattern, ($\varphi_l < \varphi_x < \varphi_h$), as stated in Lemma 2.2, always holds true. In addition to that, the symmetric steady-state equilibrium exists, such that the two countries share the same input prices, aggregate variables, and productivity cut-offs. Therefore, the relative foreign market potential is unit, $\Lambda = 1$.

Consider both home and foreign governments cooperatively and simultaneously participate in cleaning pollution by reducing the same amount of emissions permit cap. This coordinated stringent environmental policy raises the cost of emitting pollution as established in the following Proposition.

Proposition 3.1: *Under the scheme of emissions permit cap-and-trade, a reduction in emissions permit cap raises the relative permit price.*

Because the aggregate demand curve for emissions is downward sloping, a leftward shift in the inelastic supply of emissions permits leads to an excess demand, thereby bidding up the permit price relative to wage rate.

Using the above proposition and the relative equilibrium cut-offs in equations (12) and (13), the impacts of the stringent environmental policy on the *ex post* fractions of the *low* technology firms λ_l, of exporters λ_x, and of the *high* technology firms λ_h are shown in the following .

Lemma 3.1: *Under the scheme of emissions permit cap-and-trade, a reduction in emissions permit cap*

(1) *if the high technology is labor-biased (clean), reduces the fraction of the low technology firms λ_l, raises the fraction of the high technology firms λ_h, and has no effects on the fraction of exporters λ_x;*
(2) *if the high technology is emission-biased (dirty), raises the fraction of the low technology firms λ_l, reduces the fraction of the high technology firms λ_h, and has no effects on the fraction of exporters λ_x;*
(3) *if the high technology is Hicks-neutral, has no effects on the fractions of the low technology firms λ_l, exporters λ_x, and high technology firms λ_h.*

As shown in equation (12), the relative equilibrium cut-off for adopting the *low* technology and exporting (φ_l/φ_x) is independent of the environmental policy when two countries are identical. Using the Pareto productivity distribution, the *ex post* fraction of exporters is invariant to changes in the permit cap. The reason lies in that all *low* technology firms across exporting status bear the same proportional burdens of rising permit prices. Regardless of the factor-biased feature of technical change, the *ex post* fraction of exporters would not be affected by the stringent environmental policy.

Unlike the *ex post* fraction of exporters, the *ex post* fractions of firms by technology choices are affected by environmental controls. Moreover, their responses depend upon the factor-biased feature of technical change. In the presence of the labor-biased technical change, as stated in Lemma 2.1, the cost-saving advantage of adopting the *high* technology becomes more prominent as the relative emissions permit price rises. This technology adoption effect attracts more firms to upgrade to the *high* technology. Thus, the *ex post* fraction of the *low* technology firms falls, while that for the *high* technology firms rises. The cost-saving technology adoption effect reallocates market shares from the former to the latter. On the contrary, when the emission-biased technical change occurs, the cost-saving advantage is in favor of the *low* technology rather than the *high* technology, as a result of rising permit prices. More firms would prefer the initial *low* technology to the upgrading choice. Hence, the *ex post* fraction of the *low* technology firms rises, but that for the *high* technology firms falls. With the Hicks-neutral technical change, firms with the *high* technology bear the same proportional environmental pressures as firms with the *low* technology. As shown in Lemma 2.1, the cost-saving advantage of upgrading technology, captured by the relative marginal costs c_h/c_l, is invariant to the environmental instrument. In this case, the stringent environmental policy would not affect the *ex post* fractions of firms across technology choices; hence, the composition of the entire industry.

The intra-industry impacts of the stringent environmental policy on firms decisions of technology choices and selection to export are captured by changes in productivity cut-offs. In responses to a lower emissions cap, variations in the productivity cut-off of adopting the *low* technology φ_l, of exporting φ_x, and of adopting the *high* technology φ_h are associated with the factor-biased feature of technical change. This relation is expressed in the next Proposition.

Proposition 3.2: *Under the scheme of emissions permit cap-and-trade, a reduction in emissions permit cap*

(1) *if the high technology is labor-biased (clean), raises the low technology adoption productivity cut-off φ_l and the export productivity cut-off φ_x, but reduces the high technology adoption productivity cut-off φ_h;*

(2) *if the high technology is emission-biased (dirty), reduces the low technology adoption productivity cut-off* φ_l *and the export productivity cut-off* φ_x*, but raises the high technology adoption productivity cut-off* φ_h*;*
(3) *if the high technology is Hicks-neutral, has no effects on the productivity cut-offs, i.e.* φ_l*,* φ_x*, and* φ_h*.*

Proof: See Appendix. ■

The economic intuition directly comes from the general equilibrium implications for the permit input market. A reduction in the permit cap places upward pressure on the permit price relative to the wage rate. It affects all operating firms with different magnitudes across technologies, depending upon the factor-biased feature of the *high* technology relative to the *low* technology.

When the *high* technology is labor-biased, the *high* technology firms have lower cost shares of emissions permits compared with the *low* technology firms. The former suffers relatively less environmental pressures than the latter. The cost-saving advantages of adopting the *high* technology, captured by the relative marginal costs across technologies, become more prominent as the relative permit price contributes to rise. Consequently, the most productive *low* technology firms upgrade to the *high* technology, illustrated by a falling φ_h. For these *low* technology firms still unprofitable for upgrading technologies, the *low* technology requires them to substitute from cheap labor to expensive emissions permits. This factor substitution would drop the least productive firms with the *low* technology, because they are unable to earn sufficient revenues to cover their fixed production costs. Thus, φ_l rises. Similarly, for the least productive exporters with the *low* technology, an increasing permit price prevents them from entering the export market, due to negative profits. As a result, φ_x rises.

On the contrary, when the *high* technology is emission-biased, the stringent environmental control, on the one hand, raises marginal costs of production. The *high* technology firms bear more pressure from the rising permit price than the *low* technology firms, because the former has higher cost shares of emissions than the latter. For the least productive *high* technology firms, the profit for adopting the alternative *low* technology now becomes more attractive than for adopting the *high* technology. Hence, they select to downgrade to the *low* technology, captured by a higher φ_h. On the other hand, the tightened environmental policy leads to the reallocation of market shares from the *high* technology firms to the *low* technology firms. This general equilibrium effect through the rising market size favors two types of the *low* technology firms: those not in the domestic market and the most productive non-exporters. Whereas the former would decide to enter the domestic market, reflected by a lower φ_l, the latter would select to export, represented by a lower φ_x.

When the *high* technology is Hicks-neutral, both the *high* and *low* technology firms have the same cost shares for emissions permits; hence, facing the same proportional environmental burdens. The cost-saving advantage for adopting *high* technology is independent of the rising environmental pressure. The equilibrium productivity cut-off for adopting *high* technology is invariant to the tightened regulation. Resources are neither reallocated between the *high* technology and *low* technology firms, nor between exporters and non-exporters.

4. Trade liberalization

Exposure to trade occurs in the way of a lower variable trade cost, capturing the stylized fact that cross-border transportation costs have been declining over time. The effect of this trade cost reduction differs substantially from a reduction in the emissions permit cap. Trade costs are exogenous in the model; hence, are not affected by environmental policies. The variable trade cost reduction, however, has an indirect impact on the endogenous emissions permit price relative to the wage rate. This unintended environmental consequence of trade is stated as follows.

Proposition 4.1: *Under the scheme of emissions permit cap-and-trade, a reduction in variable trade costs*

(1) if the high technology is labor-biased (clean), lowers the relative aggregate demand for emissions and the relative permit price;
(2) if the high technology is emission-biased (dirty), raises the relative aggregate demand for emissions and the relative permit price;
(3) if the high technology is Hicks-neutral, has no effects on the relative aggregate demand for emissions and the relative permit price.

Proof: See Appendix. ■

With the supply of emissions permit capped at $\overline{E}$, the aggregate demand for emissions must vary with variable trade costs. The direction of this variation is associated with the factor-biased feature of technical change. A reduction in the variable trade costs brings an increasing demand from the foreign market for exporters, and creates profitable incentives of selecting to trade even for less productive local firms. This market expansion, if the *high* technology is labor-biased, increases the factor demand for labor more than for emissions permits, biding up the wage rate relative to permit price. Conversely, if the *high* technology is emission-biased, the factor demand for emissions permits increases more than the demand for labor, driving up the relative permit price. With the Hicks-neutral *high* technology in place, the factor demand for emission permits rises as much as that of labor, thereby having no impacts on the relative aggregate demand for emissions; hence, the relative factor rewards.

Although the environmental effects of trade liberalization rely on the direction of technical change, the impacts on the firm-level intra-industry dynamics are independent of this feature, as suggested from Lemma 2.1 and Proposition 4.1. As commonly seen in the Melitz-type framework, openness to trade has a positive effect on the selection to export. Moreover, in this augmented model it has an indirectly negative impact on the *high* technology adoption through its influence on the cost-saving advantage c_h/c_l. When technical change is labor-biased, the trade cost cut lowers the relative permit price as stated in Proposition 4.1. As a consequence, the cost-saving advantage for adopting the *high* technology, as noted in Lemma 2.1, falls because the *high* technology requires more cost shares of labor. Similarly, when technical change is emission-biased, exposure to trade raises the relative permit price, but still reduces the cost-saving advantage for adopting the *high* technology that demands more cost shares of emissions. Therefore, regardless of the factor-biased feature, the trade cost cut leads to the diminishing advantage of adopting the *high* technology, hence is not favorable for technology upgrading.

The relative strength between the positive effect of the selection to trade and the negative effect of the *high* technology adoption jointly determines the *ex post* fractions of the *high* technology firms λ_h and of the *low* technology firms λ_l in response to trade liberalization.

Lemma 4.1: *Under the scheme of emissions permit cap-and-trade, regardless of the factor-biased technical change, a reduction in variable trade costs raises the fraction of exporters λ_x and the fraction of the high technology firms λ_h, but reduces the fraction of the low technology firms λ_l.*

Unsurprisingly, the selection to trade resulting from the trade cost reduction induces the less productive domestic firms to enter the export market. Thus, it increases the *ex post* fraction of exporters λ_x. The effects of the openness to trade on the *ex post* fraction of firms by technology choices have two opposing effects. As a result of the positive selection to trade effect, market expansion increases profits of the *high* technology exporters from overseas markets. On the other hand, the trade liberalization has an indirectly negative impact on technology adoption through its impact on the factor market. The market expansion effect outweighs the indirect technology adoption effect, leading to a rising *ex post* fraction of the *high* technology firms λ_h, but a falling *ex post* fraction of the *low* technology firms λ_l.

Finally, the effects of the trade cost reduction on the equilibrium productivity cut-offs (i.e. φ_l, φ_x, and φ_h) are explored and summarized in the next Proposition.

Proposition 4.2: *Under the scheme of emissions permit cap-and-trade, regardless of the factor-biased technical change, a reduction in variable trade costs reduces the export productivity cut-off φ_x and high technology adoption productivity cut-off φ_h, but raises the low technology adoption productivity cut-off φ_l.*

Proof: See Appendix. ■

A reduction in the variable trade costs makes exports profitable even for the less productive firms that adopt the *low* technology and serve the domestic market only. Hence, the trade cost cut encourages them to select to export, illustrated by a falling φ_x. Resources are reallocated from non-exporters to exporters, making the least productive firms difficult to survive in the domestic market. Consequently, the equilibrium productivity cut-off for entering the market and adopting the *low* technology φ_l rises. Although the trade liberalization has an indirect negative impact on the cost-saving advantage of technology adoption, the positive effect of selection to trade raises market shares to both exporters and the *high* technology firms, and increases their profits from overseas markets. The positive effect of selection to trade plays a dominant role in raising profitable incentives for upgrading to the *high* technology, reflected by a declining φ_h, through the expanded market size.

5. Numerical simulation

The analysis so far has shown the intra-industry effects of bilateral changes in policy instruments. The welfare implications of these policy changes cannot be handled analytically, and are therefore further conducted by numerical simulation. Moreover, this numerical exercise sheds new lights on the effects of unilateral changes in the policies

Table 1. Parametric assumption.

Technology parameters		Value: Labor-biased	Value: Emission-biased
Labor coefficient α_h/α_l		1.2	1.0
Emissions coefficient β_h/β_l		1.0	1.2
Elasticity substitution between inputs η		2.0	2.0
Other assumed parameters			
Elasticity of substitution across varieties σ		4.0	4.0
Shape parameter of the Pareto distribution c		4.25	4.25
Fixed entry fee f_e		1	1
Fixed production costs with low technology f_l		1.0	1.0
Calibrated parameters			
Exogenous exit rate δ		0.55%	0.55%
Labor endowment $\overline{L}$		1363	1363
Emissions permits $\overline{E}$		688	688
Fixed export costs f_x		0.814	0.837
Variable export costs τ		1.60	1.58
Technology upgrade fixed costs f		2.17	1.49
Targets	US data	simulated values	
Annual employment-based exit rate	0.0055	0.0055	0.0055
Number of paid employees (10,000)	1363	1363	1363
Emissions (million metric tons)	688	688	688
Fraction of exporting firms	0.18	0.18	0.18
Ratio of exports to gross output	0.14	0.14	0.14
Fraction of high-tech firms	0.116	0.116	0.116

of interest, i.e. a non-coordinated environmental policy. Specifically, this section considers three numerical experiments: (1) a bilateral reduction in trade variable costs, (2) a bilateral reduction in emission cap, and (3) a unilateral reduction in emission cap by the home country only. To highlight and quantify the importance of firm-level heterogeneity in these policy scenarios, the two-country model in this paper is calibrated in a symmetric setting that reproduces some salient features of the US manufacturing industry in 2006, rather than being calibrated to particular pairs of countries.

Table 1 presents the values of parameters assumed and calibrated in the baseline. The elasticity of substitution between labor and emission on the production side is set at $\eta = 2$. With gross substitutes for the two factors, the production coefficients, $\beta_h = 1.2\beta_l = 1.2$ and $\alpha_h = \alpha_l = 1$, are adopted so that the *high* technology is labor-biased relative to the *low* technology. With the assumed coefficient values of $\beta_h = \beta_l = 1$ and $\alpha_h = 1.2\alpha_l = 1.2$, the *high* technology is emission-biased relative to the alternative choice. In line with Melitz and Redding (2015), the Pareto shape parameter of $c = 4.25$ is chosen, and the elasticity of substitution among varieties in the demand side is $\sigma = 4$. The fixed entry fee and fixed production costs with the *low* technology are normalized at one, i.e. $f_e = f_l = 1$. The exogenous exit rate of $\delta = 0.55\%$ is drawn from Atkeson and Burstein (2010).[10] Labor endowment of $\overline{L} = 1363$, obtained from the U.S. Census Bureau, is the number of employees (10,000) paid by manufactures. Total CO_2 emissions in the manufacturing industry are $\overline{E} = 668$ million metric tons reported from the U.S. Energy Information Agency (EIA).[11]

Following the calibration procedure proposed in Bernard, Redding, and Schott (2007), Atkeson and Burstein (2010), and Melitz and Redding (2015), the fixed export cost f_x, the variable export cost τ, and the technology upgrading fees f are chosen to match three observations in the US manufacturing industry: (i) the fraction of exporting firms, (ii) the share of exports in total sales, and (iii) the fraction of firms with energy-saving technologies. Bernard, Jensen, et al. (2007) suggest that around 18% of firms select to export in the manufacturing industry, and the share of export values to GDP is approximately 14%. According to the Manufacturing Energy Consumption Survey 2006 reported by the EIA, the fraction of manufacturing establishments using general energy-saving technologies is around 11.6%.[12] In the case of labor-biased technical change, $f_x = 0.814$, $\tau = 1.6$, and $f = 2.17$ are calibrated to match the above three moments of the US manufacturing industry.[13]

5.1. Numerical results

Table 2 reports the numerical results of bilateral and unilateral policy changes in a symmetric setting with two identical countries for labor-biased and emission-biased technical changes. The numerical exercises of bilateral changes in trade costs or emissions cap are meant for checking the theoretical conclusions drawn in the previous sections, while the last experiment of unilateral changes in emission cap sheds new light on the intra-industry effects of the non-coordinated climate policy.

Columns (1) and (4) consider a 10% bilateral reduction in trade variable costs, i.e. $\Delta\tau = -10\%$. As predicted in the model, the trade cost reduction slightly lowers the relative permit price to the wage rate by 0.14% compared with the baseline in the presence of the labor-biased technical change, while raising the relative permit price by 0.15% in the case of the emission-biased technical change. Regardless of this factor-biased feature, the positive effects of the trade cost cut on firms' technology upgrading choice and selection to export are consistent with the model conclusion.

In columns (2) and (5) of Table 2, a 20% bilateral reduction of emission permit caps by home and foreign countries is examined, i.e. $\Delta\overline{E} = \Delta\overline{E}^* = -20\%$. As shown in column (2) of Table 2, this coordinated stringent environmental policy raises the relative permit price by 11.66% relative to the baseline. If the *high* technology is labor-biased (clean), the rising environmental pressure drops out both the least productive *low* technology firms and the least productive exporters, as reflected by the rising cut-offs, φ_l and φ_x, by the same amount of 0.32%. Meanwhile, the increasing cost-saving advantage of the labor-biased *high* technology encourages the less productive firms to adopt the *high* technology as captured by a falling φ_h by 1.38%. In contrast, in the presence of the emission-biased technical change, as presented in column (5) of Table 2, the coordinated environmental control lowers φ_l and φ_x by 0.30%, but raises φ_h by 2.13%.

A third scenario examines a unilateral 20% reduction of emission permit cap by the home country only, i.e. $\Delta\overline{E} = -20\%$, but $\Delta\overline{E}^* = 0$. Columns (3) and (6) in Table 2 provide the corresponding results for the home and foreign variables, respectively. In the presence of labor-biased technical change, the unilateral movement towards cleaning the environment in the home country raises the relative permit price at home by 11.64%. In the home country, the cost-saving advantage of adopting *high* technology increases along with the rising environmental pressure, leading to market resources reallocation from *low*-tech firms to *high*-tech firms. Thus, the productivity cut-off of adopting the *low* technology φ_l rises by 0.53%, while the cut-off of adopting the *high* technology φ_h falls by 1.45%. This unilateral movement increases the relative foreign market potential Λ, which in turn makes the exporting market more attractive than the domestic market. As a result, the cut-off of exporting φ_x drops by 0.92%. The effect of the home environmental control

Table 2. Simulation results relative to baseline.

	Labor-biased technical change				Emission-biased technical change			
	(1)	(2)	(3)		(4)	(5)	(6)	
	$\Delta\tau=-10\%$	$\Delta\overline{E}=\Delta\overline{E}^*=-20\%$	$\Delta\overline{E}=-20\%$ home	foreign	$\Delta\tau=-10\%$	$\Delta\overline{E}=\Delta\overline{E}^*=-20\%$	$\Delta\overline{E}=-20\%$ home	foreign
Prod. cut-off of adopting low-tech φ_l	1.78%	0.32%	0.53%	−0.20%	1.79%	−0.30%	−0.06%	−0.23%
Prod. cut-off of exporting φ_x	−8.40%	0.32%	−0.92%	1.26%	−8.39%	−0.30%	−1.73%	1.47%
Prod. cut-off of adopting high-tech φ_h	−0.55%	−1.38%	−1.45%	0.08%	−0.58%	2.13%	2.03%	0.10%
Fraction of exporters λ_x	56.48%	0.00%	6.35%	−5.97%	56.48%	0.00%	7.43%	−6.91%
Fraction of high-tech firms λ_h	10.33%	7.51%	8.82%	−1.16%	10.53%	−9.74%	−8.43%	−1.37%
Relative permit price to wage p_e/w	−0.14%	11.66%	11.64%	0.02%	0.15%	11.61%	11.64%	−0.02%
Aggregate price P	−1.80%	3.24%	3.45%	1.40%	−1.79%	3.52%	3.10%	1.02%
Aggregate expenditure R	0.84%	−9.33%	−8.85%	1.10%	0.85%	−9.93%	−9.96%	0.68%
Expenditure on domestic varieties	−5.99%	−9.40%	−9.68%	1.89%	−6.12%	−9.85%	−10.76%	1.61%
Expenditure on imported varieties	42.78%	−8.85%	−3.78%	−3.78%	43.71%	−10.43%	−5.06%	−5.06%
Share of export values	41.60%	0.53%	5.56%	−4.83%	42.50%	−0.55%	5.44%	−5.70%
Market potential $RP^{\sigma-1}$	−4.52%	−0.23%	0.92%	5.41%	−4.48%	−0.09%	−1.31%	3.81%
Mass of firms M	−4.73%	−13.34%	−13.84%	0.54%	−4.74%	−11.87%	−12.45%	0.63%
Mass of low-tech firms M_l	−6.02%	−14.20%	−14.83%	0.70%	−6.06%	−10.74%	−11.48%	0.81%
Mass of high-tech firms M_h	5.12%	−6.84%	−6.24%	−0.62%	5.29%	−20.45%	−19.83%	−0.75%
Mass of exporting firms M_x	49.09%	−13.34%	−8.36%	−5.46%	49.06%	−11.87%	−5.95%	−6.33%
Mass of potential entry M_e	2.69%	−12.17%	−11.89%	−0.30%	2.70%	−12.99%	−12.67%	−0.34%
Consumption index Q^ρ	2.01%	−9.27%	−9.06%	−0.22%	2.02%	−9.91%	−9.66%	−0.26%
Consumption on domestic varieties	−4.90%	−9.35%	−9.88%	0.56%	−5.04%	−9.83%	−10.46%	0.67%
Consumption on imported varieties	44.44%	−8.79%	−4.00%	−5.04%	45.37%	−10.40%	−4.75%	−5.94%
Utility from consumption Q	2.69%	−12.17%	−11.89%	−0.30%	2.70%	−12.99%	−12.67%	−0.34%
World emissions $(\overline{E}+\overline{E}^*)$	0.00%	−20.00%	−10.00%	−10.00%	0.00%	−20.00%	−10.00%	−10.00%
Welfare $W=Q-\theta(\overline{E}+\overline{E}^*)$	13.58%	19.59%	−19.57%	39.06%	19.12%	29.71%	−28.95%	58.47%

Note: In the baseline, the productivity cut-offs are $\varphi_l=4.52$, $\varphi_x=6.77$, $\varphi_h=7.51$ in the case for labor-biased technical change; the cut-offs are $\varphi_l=4.46$, $\varphi_x=6.68$, $\varphi_h=7.41$ in the case for emission-biased technical change. $\theta(\cdot)$ takes a linear form with the marginal social carbon costs measured by the permit price relative to the aggregate price. These two prices are endogenously computed in the baseline and set constant in the remaining columns of policy scenarios. Columns (1) and (4) refer to bilateral reductions in trade variable costs by 10%; columns (2) and (5) are bilateral reductions in emissions cap by 20%; columns (3) and (6) indicate an unilateral home country emissions reduction of 20%.

on the foreign country is through the bilateral trade channel. As the relative foreign market potential rises, the export market for the foreign country becomes less attractive than the domestic market, leading to a reallocation of market shares from exporters to non-exporters. This resource reallocation discourages foreign firms to export but encourage the less productive ones to enter the domestic market, captured by a rising φ_x^* but a falling φ_l^*. The contraction of overseas market makes the technology upgrading less promising, thereby leading to a rising φ_h^*.

In the case for emission-biased technology, the unilateral environmental clean-up in the home country leads to the upward pressure of permit price, weakening the profitable incentive of technology upgrading, and reallocating resources from *high*-tech firms to *low*-tech firms. The productivity cut-off φ_l falls slightly by 0.06%, while φ_h rises by 2.03%. The tightened regulatory control makes the export market more profitable relative to the domestic market, captured by the rising relative foreign market potential Λ. As a consequence, the cut-off of exporting φ_x in the home country falls by 1.73%, while φ_x^* in the foreign country rises by 1.47%. The contraction of the overseas market in the foreign country reallocates market shares from exporters to non-exporters and from *high*-tech firms to *low*-tech firms, captured by a falling φ_l^* (by 0.23%) but a rising φ_h^* (by 0.10%). As a result of the falling input demand for emissions permits, the relative permit price falls slightly by 0.02% in the foreign country.

The welfare implications of policy variations are of interest. Social welfare could be decomposed into the utility from consumption on both domestic and imported varieties and the disutility of environmental damage arising from global CO_2 pollution. The carbon social marginal cost is measured by the emission price (relative to the aggregate price). This emission price is endogenously computed in the baseline scenario and is set constant in the scenarios of policy variations. A 10% reduction in trade variable costs contributes to welfare gains from consumption roughly by 2.69%, the magnitude of which is consistent with empirical studies summarized in Melitz and Redding (2015). A 20% bilateral reduction in emission permit cap leads to around 12% utility losses from less variety of consumption. With large enough carbon social costs, this bilateral emission cap reduction would still contribute to welfare gains. This unilateral reduction of emission permit cap by the home country makes the foreign country better off, but leads to welfare losses in the home country. The former benefits from the substantial reduction in global pollution damage, while the latter experiences the drastic decline in consumption of varieties.

6. Conclusions

This paper augments the Melitz-type trade model by accounting for both environmental pollution and factor-biased technology choices. Using the extended model, this paper examines the impact of stringent environmental policies and openness to trade on technology adoption and trade decisions of heterogeneous firms, thereby making inference about the composition of the entire industry and the environment.

Some novel conclusions are obtained. Implementation of the stringent environmental policy by reducing the emission permit cap has different effects on firms' decisions, varying with the factor-biased technology feature. When the *high* technology is labor-biased (clean), a lower permit cap serves to reallocate resources from the *low* technology firms to the *high* technology firms. This resource reallocation encourages firms to adopt the emission-saving *high* technology, but discourages the least productive firms to enter the market. The entire industry is composed of more *high* technology firms, but less *low* technology firms. It also experiences gains from the improved aggregate productivity by driving out the least productive firms. When the emission-biased technical change occurs, the induced reallocation of resources goes in the opposite direction. In the presence of the Hicks-neutral *high* technology, the tightened environmental policy has no impacts on resource reallocation between the *high* and *low* technology firms and between exporters and non-exporters.

This paper also sheds light on the environmental impact of openness to trade at both industry and firm levels. At the aggregate level, when the labor-biased (emission-biased) *high* technology is in place, the trade cost cut reduces (raises) the aggregate demand for emissions permits more than labor, driving down (biding up) the relative permit price to wage rate. When the *high* technology is Hicks-neutral, openness to trade does not alter the aggregate demand of emissions. Whereas the lower variable trade cost generates a positive selection to export effect but a negative technology adoption effect, the ultimate effects on firm decisions of technology upgrading and selection to trade are independent of the factor-biased technical change. Whereas exposure to trade drops out the least productive firms from the domestic market, it induces firms to export and adopt the *high* technology.

Furthermore, this paper calibrates and simulates the model to demonstrate the quantitative results of bilateral and unilateral policy variations in trade variable costs and the environmental instrument. With sufficient weight of clean environment on the social welfare, bilateral emission cap reductions could be welfare-enhancing. A unilateral movement towards cleaning the environment has profound policy implications. The unilateral action leads to substantial welfare losses from consumption varieties in the home country, while provides a free-riding opportunity for the foreign country in terms of welfare gains.

Notes

1. For example, the US manufactures contribute to roughly 70% of the total value of exports reported by the U.S. Bureau of Economics Analysis, while they also emit around one-fourth of the total amount of air pollutants as estimated by the U.S. Environmental Protection Agency.
2. Levinson (2009) suggests that technology improvement has mainly contributed to the clean-up of air emissions in the US manufacturing industry from 1987 to 2001. His recent work (Levinson 2014) shows that the estimated production technique effect accounts for more than 90% of air clean-up.
3. See a review paper by Jaffe, Newell, and Starvins (2003).
4. Galdeano-Gomez (2010) analyzes the effects of export orientation on firm productivity differences accounting for environmental productivity, using panel data in the Spanish food industry. Girma and Hanley (2015)'s findings suggest that exporters are more likely to denote their innovation as having positive environmental effects than non-exporters from the UK firms. Cui et al. (2016) document a negative correlation between facility productivity and criteria air emissions per sale in the US manufacturing sector. Cao et al. (2016) apply the Chinese firm panel data and document an inverted U-shape relationship between productivity and environmental performance. Holladay (2016) finds that exporters are environmentally friendlier than non-exporters in the US manufacturing industry in terms of toxic pollution per sale.
5. I thank the anonymous referee for pointing this out.
6. Note, $c > 0$ is a shape parameter that determines the skewness of the Pareto distribution, assuming $c > \sigma - 1$ so the variance of log productivity is finite, in which the term $\varphi^{\sigma-1}g(\varphi) = \xi h(\varphi)$, where $h(\varphi) = \gamma\varphi^{-(\gamma+1)}$ and $\xi \equiv c/\gamma$. The corresponding cumulative distribution follows a Pareto distribution with a form of $H(\varphi) = 1 - \varphi^{-\gamma}$, where $\gamma \equiv c - \sigma + 1 > 0$.

7. Without loss of generality, $\alpha_h = \alpha_l$ and $\beta_h > \beta_l$ imply that the *high* technology is emission-augmenting technical change relative to the *low* technology; $\alpha_h > \alpha_l$ and $\beta_h = \beta_l$ imply the labor-augmenting technical change; and $\beta_h/\beta_l = \alpha_h/\alpha_l > 1$ refer to the Hicks-neutral technical change. With the elasticity of substitution between labor and emissions inputs, the factor-augmenting technical change could be related to the factor-biased technical change. If the two factors are gross substitutes ($\eta > 1$), labor-augmenting technical change is also labor-biased. In contrast, if the factors are gross complements ($\eta < 1$), labor-augmenting technical change is then emission-biased.
8. This partition pattern is consistent with the empirical evidence on technology choices of the Argentinean manufacturing firms as found in Bustos (2011b). With alternative assumptions on parameters and cost structure, one could have that all exporters are clean firms, while only a fraction of non-exporters adopts the clean technology. In this case, the mathematical formula for productivity cut-offs of exporting and of adopting technologies are redefined as follows: $\pi_{ld}(\hat{\varphi}_l) = 0$, $\pi_{hx}(\hat{\varphi}_x) = 0$, and $\pi_{hd}(\hat{\varphi}_h) - \pi_{ld}(\hat{\varphi}_h) = 0$;thus, $\hat{\varphi}_l < \hat{\varphi}_h < \hat{\varphi}_x$.
9. In the case of a CD technology function as in Bustos (2011a), the monotonic property of the aggregate demand of factor holds in this paper.
10. Atkeson and Burstein (2010) find that the exogenous exit rate, $\delta = 0.55\%$, is consistent with the rate for large firms with more than 500 employees in the US data. In addition, this value also captures the exogenous bad shock to firms whose productivity is far from the productivity cut-off of exiting the market.
11. Total emissions are calculated from energy consumption by fuel type and by sub-industry section multiplied by the corresponding CO_2 emissions rates by fuel type. Energy consumptions by fuel type and by sub-industry data are from Manufacturing Energy Consumption Survey 2006 in the EIA, Table 1.2 of 'First Use of Energy for All Purposes (Fuel and Nonfuel) by NAICS, Unit: Trillion Btu'. CO_2 emission rates by fuel type are obtained from table of 'CO_2 Emissions Coefficients by Fuel Energy 1980-2008, Unit: Million Metric Tons CO_2 per Quadrillion Btu' by the EPA.
12. The energy-saving technologies include the following five specific technologies: Computer Control of Building Wide Environment, Computer Control of Process or Major Energy-Using Equipment, Waste Heat Recovery, Adjustable - Speed Motors, and Oxy - Fuel Firing. For detailed information, please see Table 8.2, 'Number of Establishments by Usage of General Energy-Saving Technologies'.
13. In the case of emission-biased technical change, $f_x = 0.837$, $\tau = 1.58$, and $f = 1.49$ are chosen to match the three moments of the US manufacturing industry.

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References

Acemoglu, D. 2002. "Directed Technical Change." *Review of Economic Studies* 69(4): 781–809.

Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous. 2012. "The Environment and Directed Technical Change." *American Economic Review* 102(1): 131–66.

Antweiler, W., B. R. Copeland, and M. S. Taylor. 2001. "Is Free Trade Good for the Environment?" *American Economic Review* 91(4): 877–908.

Atkeson, A., and A. T. Burstein. 2010. "Innovation, Firm Dyanmics, and International Trade." *Journal of Political Economy* 118(3): 433–484.
Bas, M. 2012. "Technology Adoption, Export Status, and Skill Upgrading: Theory and Evidence." *Review of International Economics* 20(2): 315–331.
Bernard, A. B., J. Eaton, J. B. Jensen, and S. Kortum. 2003. "Plants and Productivity in International Trade." *American Economic Review* 93(4): 1268–1290.
Bernard, A. B., J. B. Jensen, S. J. Redding, and P. K. Schott. 2007. "Firms in International Trade." *Journal of Economic Perspectives* 21(3): 105–130.
Bernard, A. B., S. J. Redding, and P. K. Schott. 2007. "Comparative Advantage and Heterogeneous Firms." *Review of Economics Studies* 74(1): 31–66.
Bustos, P. 2011a. "The Impact of Trade Liberalization on Skill Upgrading Evidence from Argentina." Working Paper No. 559, Barcelona Graduate School of Economics, Barcelona.
Bustos, P. 2011b. "Trade Liberalization, Exports, and Technology Upgrading: Evidence on the Impact of MERCOSUR on Argentinian Firms." *American Economic Review* 101(1): 304-340.
Cao, J., L. D. Qiu, and M. Zhou. 2016. "Who Invest More in Advanced Abatement Technology: Theory and Evidence." *Canadian Journal of Economics* 49(2): 637–672.
Copeland, B. R., and M. S. Taylor. 1994. "North-South Trade and the Environment." *Quarterly Journal of Economics* 109(3): 755–788.
Copeland, B. R., and M. S. Taylor. 1995. "Trade and Transboundary Pollution." *American Economic Review* 85(4): 716–737.
Cui, J., H. Lapan, and G. Moschini. 2016. "Productivity, Export, and Environmental Performance: Air Pollutants in the United States." *American Journal of Agricultural Economics* (2): 447–467.
Dixit, A. K., and J. E. Stiglitz. 1977. "Monopolistic Competition and Optimum Product Diversity." *American Economic Review* 67(3): 297–308.
Erdogan, A. 2014. "Bilateral Trade and the Environment: A General Equilibrium Model Based on New Trade Theory." *International Review of Economics & Finance* 34: 52–71.
Forslid, R., T. Okubo, and K.-H. Ulltveit-Moe. 2014. "International Trade, CO_2 Emissions and Heterogeneous Firms." CESifo Working Paper No. 4817, University of Munich, Munich.
Frankel, J. A., and A. K. Rose. 2005. "Is Trade Good or Bad for the Environment? Sorting out the Causality." *Review of Economics and Statistics* 87(1): 85–91.
Galdeano-Gomez, E. 2010. "Exporting and Environmental Performance: A Firm-level Productivity Analysis." *The World Economy* 33(1): 60–88.
Girma, S., and A. Hanley. 2015. "How Green are Exporters?" *Scottish Journal of Political Economy* 62(3): 291–309.
Greenstone, M., J. A. List, and C. Syverson. 2012. "The Effects of Environmental Regulation on the Competitiveness of U.S. Manufacturing." Working Paper No. 18392, National Bureau of Economic Research, Cambridge, MA.
Grimaud, A., and L. Rouge. 2008. "Environment, Directed Technical Change and Economic Policy." *Environmental & Resource Economics* 41(4): 439–463.
Holladay, S. J. 2016. "Exporters and the Environment." *Canadian Journal of Economics* 49(1): 147–172.
Jaffe, A. B., R. G. Newell, and R. N. Starvins. 2003. "Technological Change and the Environment." In *Handbook of Environmental Economics*, edited by K. G. Maler and J. R. Vincent, 1st ed., Vol. 1, 461–516. Amsterdam, the Netherlands: Elsevier.
Konishi, Y., and N. Tarui. 2015. "Intra-Industry Reallocations and Long-run Impacts of Environmental Regulations." *Journal of the Association of Environmental and Resource Economists* 2(1): 1–42.
Kreickemeier, U., and P. M. Richter. 2014. "Trade and the Environment: The Role of Firm Heterogeneity." *Review of International Economics* 22(2): 209–225.
Levinson, A. 2009. "Technology, International Trade, and Pollution from US Manufacturing." *American Economic Review* 99(5): 2177–2192.
Levinson, A. 2014. "A Direct Estimate of the Technique Effect: Changes in the Pollution Intensity of US Manufacturing 1990-2008." Working Paper No. 20399, National Bureau of Economic Research, Cambridge, MA.
Levinson, A., and M. S. Taylor. 2008. "Unmasking The Pollution Haven Effect." *International Economic Review* 49(1): 223–254.
Managi, S., A. Hibiki, and T. Tsurumi. 2009. "Does Trade Openness Improve Environmental Quality?" *Journal of Environmental Economics and Management* 58(3): 346–363.

McAusland, C., and D. L. Millimet. 2013. "Do National Borders Matter? Intranational Trade, International Trade, and the Environment." *Journal of Environmental Economics and Management* 65(3): 411–437.
Melitz, M. J. 2003. "The Impact of Trade on Intra-Industry Reallocations and Aggregate Industry Productivity." *Econometrica* 71(6): 1695–1725.
Melitz, M. J., and S. J. Redding. 2015. "New Trade Models, New Welfare Implications." *The American Economic Review* 105(3): 1105–1146.
Okubo, T. 2009. "Firm Heterogeneity and Ricardian Comparative Advantage within and Across Sectors." *Economic Theory* 38(3): 533–559.
Tybout, J. R. 2003. "Plant- and Firm-Level Evidence on New Trade Theories." In *Handbook of International Trade*, edited by E. K. Choi and J. Harrigan, 338–415. Oxford, UK: Blackwell Publishing.
Unel, B. 2013. "The Interaction Between Technology Adoption and Trade When Firms Are Heterogeneous." *Review of International Economics* 21(4): 797–808.
Yokoo, H.-F. 2009. "Heterogeneous Firms, the Porter Hypothesis, and Trade." Unpublished manuscript, Kyoto University, Kyoto.

Appendix

Proof of Lemma 2.1: The relationship between the relative marginal costs (c_l/c_h) and the relative permit price could be linked with the difference in cost shares across technologies:

$$\frac{\partial(c_l/c_h)}{\partial p_e} = \frac{c_l}{p_e c_h}\left(\frac{\partial c_l}{\partial p_e}\frac{p_e}{c_l} - \frac{\partial c_h}{\partial p_e}\frac{p_e}{c_h}\right)$$
$$= \frac{c_l}{p_e c_h}\left(s_l^e - s_h^e\right)\begin{cases} > 0 & \text{if labor-biased } (s_l^e > s_h^e) \\ < 0 & \text{if emission-biased } (s_l^e < s_h^e) \\ = 0 & \text{if Hicks-neutral } (s_l^e = s_h^e) \end{cases}$$

Thus, $\text{sign}(\frac{\partial(c_l/c_h)}{\partial p_e}) = \text{sign}(s_l^e - s_h^e)$. ■

Proof of Proposition 2.1: This part examines the monotonicity of the relative aggregate demand of emissions to labor. Consider the relative aggregate demand for emissions and labor:

$$\left(\frac{E}{L}\right)^D = \frac{M\left\{\int_{\varphi_l}^{\varphi_h} e_{ld}(\varphi)\mu(\varphi)d\varphi + \int_{\varphi_x}^{\varphi_h} e_{lx}(\varphi)\mu(\varphi)d\varphi + \int_{\varphi_h}^{\infty}[e_{hd}(\varphi)+e_{hx}(\varphi)]\mu(\varphi)d\varphi\right\}}{M\left\{\int_{\varphi_l}^{\varphi_h} l_{ld}(\varphi)\mu(\varphi)d\varphi + \int_{\varphi_x}^{\varphi_h} l_{lx}(\varphi)\mu(\varphi)d\varphi + \int_{\varphi_h}^{\infty}[l_{hd}(\varphi)+l_{hx}(\varphi)]\mu(\varphi)d\varphi\right\}}$$
$$= \left(\frac{w}{p_e}\right)\frac{s_l^e\int_{\varphi_l}^{\varphi_h} r_{ld}(\varphi)\mu(\varphi)d\varphi + s_l^e\int_{\varphi_x}^{\varphi_h} r_{lx}(\varphi)\mu(\varphi)d\varphi + s_h^e\int_{\varphi_h}^{\infty}[r_{hd}(\varphi)+r_{hx}(\varphi)]\mu(\varphi)d\varphi}{s_l^l\int_{\varphi_l}^{\varphi_h} r_{ld}(\varphi)\mu(\varphi)d\varphi + s_l^l\int_{\varphi_x}^{\varphi_h} r_{lx}(\varphi)\mu(\varphi)d\varphi + s_h^l\int_{\varphi_h}^{\infty}[r_{hd}(\varphi)+r_{hx}(\varphi)]\mu(\varphi)d\varphi}$$
$$= \left(\frac{w}{p_e}\right)\frac{s_l^e\int_{\varphi_l}^{\varphi_h}\varphi^{\sigma-1}g(\varphi)d\varphi + s_l^e\left(\frac{r_{lx}}{r_{ld}}\right)\int_{\varphi_x}^{\varphi_h}\varphi^{\sigma-1}g(\varphi)d\varphi + s_h^e\left(\frac{r_{hd}}{r_{ld}}+\frac{r_{hx}}{r_{ld}}\right)\int_{\varphi_h}^{\infty}\varphi^{\sigma-1}g(\varphi)d\varphi}{s_l^l\int_{\varphi_l}^{\varphi_h}\varphi^{\sigma-1}g(\varphi)d\varphi + s_l^l\left(\frac{r_{lx}}{r_{ld}}\right)\int_{\varphi_x}^{\varphi_h}\varphi^{\sigma-1}g(\varphi)d\varphi + s_h^l\left(\frac{r_{hd}}{r_{ld}}+\frac{r_{hx}}{r_{ld}}\right)\int_{\varphi_h}^{\infty}\varphi^{\sigma-1}g(\varphi)d\varphi}$$

Because productivity follows the Pareto distribution, $g(\varphi) = c\varphi^{-c-1}$, we could derive $\int_{\varphi_i}^{\varphi_j}\varphi^{\sigma-1}g(\varphi)d\varphi = c(\varphi_i^{-\gamma} - \varphi_j^{-\gamma})/\gamma$ and $\int_{\varphi_i}^{\infty}\varphi^{\sigma-1}g(\varphi)d\varphi = c\varphi_i^{-\gamma}/\gamma$, where $\gamma \equiv c - \sigma + 1 > 0$. In addition, $r_{jx} = r_{jd}\tau^{1-\sigma}$ and $r_{hd} = r_{ld}(c_l/c_h)^{\sigma-1}$. Recall $\lambda_x = \left(\frac{\varphi_x}{\varphi_l}\right)^{-c}$, $\lambda_h = \left(\frac{\varphi_h}{\varphi_l}\right)^{-c}$, and the relative productivity cut-offs in equations (12) and (14), thus, the relative aggregate demand for emissions to labor is

$$\left(\frac{E}{L}\right)^D = \left(\frac{w}{p_e}\right)\frac{s_l^e(\varphi_l^{-\gamma}-\varphi_h^{-\gamma})+s_l^e\tau^{1-\sigma}(\varphi_x^{-\gamma}-\varphi_h^{-\gamma})+s_h^e\left(\frac{c_l}{c_h}\right)^{\sigma-1}(1+\tau^{1-\sigma})\varphi_h^{-\gamma}}{s_l^l(\varphi_l^{-\gamma}-\varphi_h^{-\gamma})+s_l^l\tau^{1-\sigma}(\varphi_x^{-\gamma}-\varphi_h^{-\gamma})+s_h^l\left(\frac{c_l}{c_h}\right)^{\sigma-1}(1+\tau^{1-\sigma})\varphi_c^{-\gamma}}$$
$$= \frac{ws_l^e}{p_e s_l^l}\left\{1+\left(\frac{s_h^e}{s_l^e}-\frac{s_h^l}{s_l^l}\right)\frac{s_l^l}{s_h^l}\left[1+\frac{s_l^l}{s_h^l}A\right]^{-1}\right\}$$

where $A \equiv (\frac{\lambda_x f_x}{\lambda_h f}+\frac{f_l}{\lambda_h f})[1-(\frac{c_l}{c_h})^{1-\sigma}]-(\frac{c_l}{c_h})^{1-\sigma}$. ■

Due to the CES production function, $s_j^e = [\frac{\beta_j c_j(w,p_e)}{p_e}]^{\eta-1}$, $\frac{s_h^e}{s_l^e} = (\frac{\beta_l c_l}{\beta_h c_h})^{1-\eta}$, $\frac{s_h^l}{s_l^l} = (\frac{\alpha_l c_l}{\alpha_h c_h})^{1-\eta}$, and $\frac{s_l^e}{s_l^l} = (\frac{\beta_l}{\alpha_l}\frac{w}{p_e})^{\eta-1}$. The relative aggregate input demand is

$$\left(\frac{E}{L}\right)^D = \left(\frac{w}{p_e}\right)^\eta\left(\frac{\beta_l}{\alpha_l}\right)^{\eta-1}\left\{1+\left[\left(\frac{\beta_l\alpha_h}{\beta_h\alpha_l}\right)^{1-\eta}-1\right]\left[1+\left(\frac{\alpha_l c_l}{\alpha_h c_h}\right)^{\eta-1}A\right]^{-1}\right\}$$

where $A \equiv (\frac{\lambda_x f_x}{\lambda_h f}+\frac{f_l}{\lambda_h f})[1-(\frac{c_l}{c_h})^{1-\sigma}]-(\frac{c_l}{c_h})^{1-\sigma}$.

To examine the monotonicity of the relative aggregate demand, it is suffice to check the monotonicity of $A(\frac{c_l}{c_h})^{\eta-1}$ w.r.t. the relative input price w/p_e.

$$A\left(\frac{c_l}{c_h}\right)^{\eta-1} = \frac{(c_l/c_h)^{\eta-\sigma}}{(1+\tau^{1-\sigma})}\left\{\left(\frac{\varphi_l}{\varphi_h}\right)^{-\gamma}-1+\tau^{1-\sigma}\left[\left(\frac{\varphi_x}{\varphi_h}\right)^{-\gamma}-1\right]\right\}$$

From the relative cut-offs in equations (13) and (14), it is easy to see that $\frac{\partial(\varphi_l/\varphi_h)}{\partial(c_l/c_h)} > 0$ and $\frac{\partial(\varphi_x/\varphi_h)}{\partial(c_l/c_h)} > 0$. Given $\gamma > 0$, one could show $\frac{\partial A(c_l/c_h)^{\eta-1}}{\partial(c_l/c_h)} < 0$, if $\sigma > \eta$; $\frac{\partial A(c_l/c_h)^{\eta-1}}{\partial(c_l/c_h)} > 0$, if $\sigma < \eta$; and $\frac{\partial A(c_l/c_h)^{\eta-1}}{\partial(c_l/c_h)} = 0$, if $\sigma = \eta$.

When technical change is Hicks-neutral (i.e. $\beta_h/\beta_l = \alpha_h/\alpha_l > 1$), the relative aggregate factor demand is $(\frac{E}{L})^D = (\frac{w}{p_e})^\eta(\frac{\beta_l}{\alpha_l})^{\eta-1}$, so $\frac{\partial(\frac{E}{L})^D}{\partial(p_e/w)} < 0$.

When technical change is labor-biased, i.e. labor-augmenting with gross substitute inputs ($\alpha_h > \alpha_l, \beta_h = \beta_l, \eta > 1$), or emission-augmenting with gross complement inputs ($\alpha_h = \alpha_l, \beta_h > \beta_l, \eta < 1$):

$$\frac{\partial(c_l/c_h)}{\partial(p_e/w)} > 0 \Rightarrow \text{ if } \sigma \geq \eta, \frac{\partial A(c_l/c_h)^{\eta-1}}{\partial(p_e/w)} = \frac{\partial A(c_l/c_h)^{\eta-1}}{\partial(c_l/c_h)}\frac{\partial(c_l/c_h)}{\partial(p_e/w)} \leq 0$$
$$\left(\frac{\beta_l\alpha_h}{\beta_h\alpha_l}\right)^{1-\eta} < 1 \Rightarrow \frac{\partial(\frac{E}{L})^D}{\partial(p_e/w)} < 0$$

When technical change is emission-biased, i.e. emission-augmenting with gross substitute inputs ($\alpha_h = \alpha_l, \beta_h > \beta_l, \eta > 1$), or labor-augmenting with gross complement inputs ($\alpha_h > \alpha_l, \beta_h = \beta_l, \eta < 1$):

$$\frac{\partial(c_l/c_h)}{\partial(p_e/w)} < 0 \Rightarrow \text{ if } \sigma \geq \eta, \frac{\partial A(c_l/c_h)^{\eta-1}}{\partial(p_e/w)} = \frac{\partial A(c_l/c_h)^{\eta-1}}{\partial(c_l/c_h)}\frac{\partial(c_l/c_h)}{\partial(p_e/w)} \geq 0$$
$$\left(\frac{\beta_l\alpha_h}{\beta_h\alpha_l}\right)^{1-\eta} > 1 \Rightarrow \frac{\partial(\frac{E}{L})^D}{\partial(p_e/w)} < 0$$

To sump up, the relative aggregate factor demand $(E/L)^D$ decreases in the relative factor price (p_e/w), if $\sigma \geq \eta > 0$.

Proof of Proposition 3.2: This part examines the effects of a stringent environmental regulation on the equilibrium productivity cut-offs. Using the free entry conditions and relative productivity cut-offs, one could solve the equilibrium cut-offs as functions of endogenous input prices and other parameters. First, recall the free entry condition (15):

$$f_l \int_{\varphi_l}^{\infty} \left(\frac{\varphi}{\varphi_l}\right)^{\sigma-1} g(\varphi)d\varphi + f_x \int_{\varphi_x}^{\infty} \left(\frac{\varphi}{\varphi_x}\right)^{\sigma-1} g(\varphi)d\varphi + f \int_{\varphi_h}^{\infty} \left(\frac{\varphi}{\varphi_h}\right)^{\sigma-1} g(\varphi)d\varphi$$
$$= \delta f_e + f_l \int_{\varphi_d}^{\infty} g(\varphi)d\varphi + f_x \int_{\varphi_x}^{\infty} g(\varphi)d\varphi + f \int_{\varphi_h}^{\infty} g(\varphi)d\varphi$$

With the Pareto distribution of productivity, $G(\varphi) = 1 - \varphi^{-c}$, $\int_{\varphi_i}^{\infty} dG(\varphi) = \varphi_i^{-c}$, and $\int_{\varphi_i}^{\infty} (\varphi/\varphi_i)^{\sigma-1}\, dG(\varphi) = c\varphi_i^{-c}/\gamma$, where $\gamma \equiv c - \sigma + 1 > 0$. The above free entry condition could be further simplified:

$$\frac{\sigma - 1}{c - \sigma + 1} \left\{ f_l + f_x \left(\frac{\varphi_x}{\varphi_l}\right)^{-c} + f \left(\frac{\varphi_h}{\varphi_l}\right)^{-c} \right\} = \delta f_e \varphi_l^c$$

Recall $\lambda_x \equiv \left(\frac{\varphi_x}{\varphi_l}\right)^{-c}$ and $\lambda_h \equiv \left(\frac{\varphi_h}{\varphi_l}\right)^{-c}$ as the *ex post* fractions of exporters and *high* technology firms, respectively. Using the relative productivity cut-offs in equations (12) and (14), one could solve the equilibrium productivity cut-offs:

$$\varphi_l = \Psi \left\{ f_l + \lambda_x f_x + \lambda_h f \right\}^{1/c}$$
$$\varphi_x = (\lambda_x)^{-1/c}\varphi_l = \Psi \left\{ \frac{1}{\lambda_x} f_l + f_x + \frac{\lambda_h}{\lambda_x} f \right\}^{1/c}$$
$$\varphi_h = (\lambda_h)^{-1/c}\varphi_l = \Psi \left\{ \frac{1}{\lambda_h} f_l + \frac{\lambda_x}{\lambda_h} f_x + f \right\}^{1/c}$$

where $\Psi \equiv \left(\frac{1}{\delta f_e} \frac{\sigma-1}{c-\sigma+1}\right)^{1/c}$. ■

Using the relative equilibrium cut-offs, the *ex post* fractions of the *high* technology firms and exporters are, respectively

$$\lambda_h = \left(\frac{\varphi_h}{\varphi_l}\right)^{-c} = \left\{ \left[\left(\frac{c_l}{c_h}\right)^{\sigma-1} - 1 \right] \left(1 + \tau^{1-\sigma}\right) \frac{f_l}{f} \right\}^{c/(\sigma-1)}$$
$$\lambda_x = \left(\frac{\varphi_x}{\varphi_l}\right)^{-c} = \tau^{-c} \left(\frac{f_x}{f_l}\right)^{-c/(\sigma-1)}$$

Thus, the effects of the stringent environmental policy on these two *ex post* fractions are:

$$\frac{\partial \lambda_x}{\partial p_e} = 0;\ \text{sign}\left(\frac{\partial \lambda_h}{\partial p_e}\right) = \text{sign}\left(\frac{\partial c_l/c_h}{\partial p_e}\right) \begin{cases} > 0 & \text{if labor-biased } (s_l^e > s_h^e) \\ = 0 & \text{if Hicks-neutral } (s_l^e = s_h^e) \\ < 0 & \text{if emission-biased } (s_l^e < s_h^e) \end{cases}$$

Using the equilibrium productivity cut-offs provided above, therefore, the effects of the tightened environmental control on productivity cut-offs are

$$\text{sign}\left(\frac{\partial \varphi_l}{\partial p_e}\right) = \text{sign}\left(\frac{\partial \lambda_h}{\partial p_e}\right);\ \text{sign}\left(\frac{\partial \varphi_x}{\partial p_e}\right) = \text{sign}\left(\frac{\partial \lambda_h}{\partial p_e}\right);\ \text{sign}\left(\frac{\partial \varphi_h}{\partial p_e}\right) = -\text{sign}\left(\frac{\partial \lambda_h}{\partial p_e}\right)$$

where $\text{sign}(\frac{\partial \lambda_h}{\partial p_e})$ depends on the factor-biased technical change as shown above.

Proof of Proposition 4.1: This part examines the effects of a trade cost reduction on the relative input prices. Recall the factor market clear conditions $(\frac{\bar{E}}{\bar{L}})^S = (\frac{E}{L})^D(\frac{p_e}{w})$. Total differentiation gives rise to

$$\frac{\partial\, (E/L)^D}{\partial (p_e/w)} d\left(\frac{p_e}{w}\right) + \frac{\partial\, (E/L)^D}{\partial \tau} d\tau = 0 \Rightarrow \frac{\partial (p_e/w)}{\partial \tau} = -\frac{\partial (E/L)^D/\partial \tau}{\partial (E/D)^D/\partial (p_e/w)}$$

$$\text{since } \frac{\partial (E/D)^D}{\partial (p_e/w)} < 0 \Rightarrow \text{sign}\left(\frac{\partial p_e/w}{\partial \tau}\right) = \text{sign}\left(\frac{\partial (E/L)^D}{\partial \tau}\right)$$

Recall the relative aggregate input demand:

$$\left(\frac{E}{L}\right)^D = \left(\frac{w}{p_e}\right)^\eta \left(\frac{\beta_l}{\alpha_l}\right)^{\eta-1} \left\{1 + \left[\left(\frac{\beta_l \alpha_h}{\beta_h \alpha_l}\right)^{1-\eta} - 1\right]\left[1 + \left(\frac{\alpha_l c_l}{\alpha_h c_h}\right)^{\eta-1} A\right]^{-1}\right\}$$

where $A \equiv (\frac{\lambda_x f_x}{\lambda_h f} + \frac{f_l}{\lambda_h f})[1 - (\frac{c_l}{c_h})^{1-\sigma}] - (\frac{c_l}{c_h})^{1-\sigma}$. If technical change is Hicks-neutral, $(\frac{E}{L})^D = (\frac{w}{p_e})^\eta (\frac{\beta_l}{\alpha_l})^{\eta-1}$, thus, $\frac{\partial (p_e/w)}{\partial \tau} = 0$. If technical change is labor-biased, then $(\frac{\beta_l \alpha_h}{\beta_h \alpha_l})^{1-\eta} - 1 < 0$. Conditional on p_e/w, the partial derivative of $\frac{\lambda_x f_x}{\lambda_h f} + \frac{f_l}{\lambda_h f}$ w.r.t. τ is determined as follows:

$$\frac{\lambda_x f_x}{\lambda_h f} + \frac{f_l}{\lambda_h f} = \left[\left(\frac{c_l}{c_h}\right)^{\sigma-1} - 1\right]^{\frac{c}{1-\sigma}} f^{\frac{\gamma}{\sigma-1}} (1 + \tau^{1-\sigma})^{\frac{c}{1-\sigma}} \left[\tau^{-c} f_x^{\frac{\gamma}{1-\sigma}} + f_l^{\frac{\gamma}{1-\sigma}}\right]$$

$$\frac{\partial (\frac{\lambda_x f_x}{\lambda_h f} + \frac{f_l}{\lambda_h f})}{\partial \tau}|_{p_e/w} = \left[\left(\frac{c_l}{c_h}\right)^{\sigma-1} - 1\right]^{\frac{c}{1-\sigma}} f^{\frac{\gamma}{\sigma-1}} c (1 + \tau^{1-\sigma})^{\frac{\gamma}{1-\sigma}} \tau^{-c} \left[f_l^{\frac{\gamma}{1-\sigma}} - \tau^{-\gamma} f_x^{\frac{\gamma}{1-\sigma}}\right] > 0$$

The above inequality holds true as long as $\varphi_x > \varphi_l$, that is, $\tau f_x^{\frac{1}{\sigma-1}} > f_l^{\frac{1}{\sigma-1}}$. Thus, conditional on p_e/w

$$\text{sign}\left(\frac{\partial (E/L)^D}{\partial \tau}|_{p_e/w}\right) = \text{sign}\left(\frac{\partial A}{\partial \tau}|_{p_e/w}\right) = \text{sign}\left(\frac{\partial (\frac{\lambda_x f_x}{\lambda_h f} + \frac{f_l}{\lambda_h f})}{\partial \tau}|_{p_e/w}\right) > 0$$

$$\Rightarrow \frac{\partial (p_e/w)}{\partial \tau} > 0$$

If technical change is emission-biased, then $(\frac{\beta_l \alpha_h}{\beta_h \alpha_l})^{1-\eta} - 1 > 0$. Given p_e/w

$$\text{sign}\left(\frac{\partial (E/L)^D}{\partial \tau}|_{p_e/w}\right) = -\text{sign}\left(\frac{\partial A}{\partial \tau}|_{p_e/w}\right) = -\text{sign}\left(\frac{\partial (\frac{\lambda_x f_x}{\lambda_h f} + \frac{f_l}{\lambda_h f})}{\partial \tau}|_{p_e/w}\right) < 0$$

$$\Rightarrow \frac{\partial (p_e/w)}{\partial \tau} < 0$$

In sum, the effects of the trade cost reduction on the relative permit price vary with the factor-biased feature of technical change:

$$\frac{\partial(p_e/w)}{\partial\tau}\begin{cases} >0 & \text{if labor-biased} \\ <0 & \text{if emission-biased} \\ =0 & \text{if Hicks-neutral}\end{cases}$$

■

Proof of Proposition 4.2: This part investigates the effects of a trade cost reduction on productivity cut-offs. Take derivative of the relative input market clear conditions $(\frac{\bar{E}}{\bar{L}})^S = (\frac{E}{L})^D(\frac{p_e}{w}, A)$ w.r.t. τ:

$$0=\frac{\partial(\bar{E}/\bar{L})^S}{\partial\tau}=\frac{\partial(E/L)^D}{\partial(p_e/w)}\frac{\partial(p_e/w)}{\partial\tau}+\frac{\partial(E/L)^D}{\partial A}\frac{\partial A}{\partial\tau}$$

where $A\equiv(\frac{\lambda_x f_x}{\lambda_h f}+\frac{f_l}{\lambda_h f})[1-(\frac{c_l}{c_h})^{1-\sigma}]-(\frac{c_l}{c_h})^{1-\sigma}$. First, the relative aggregate demand of inputs decreases as the relative permit price rises, regardless of the factor-biased technical change, that is, $\frac{\partial(E/L)^D}{\partial(p_e/w)}<0$. Next, using the above partial derivative, one could show $\frac{\partial A}{\partial\tau}>0$. Because when technical change is labor-biased, $\frac{\partial(p_e/w)}{\partial\tau}>0$ and $\frac{\partial(E/L)^D}{\partial A}>0$ imply $\frac{\partial A}{\partial\tau}>0$; when it is emission-biased, $\frac{\partial(p_e/w)}{\partial\tau}<0$ and $\frac{\partial(E/L)^D}{\partial A}<0$ also suggest $\frac{\partial A}{\partial\tau}>0$. Regardless of the factor-biased feature of technical change, $\frac{\partial(c_l/c_h)}{\partial\tau}=\frac{\partial(c_l/c_h)}{\partial(p_e/w)}\frac{\partial(p_e/w)}{\partial\tau}\geq 0$. Thus, $\text{sign}(\partial(\frac{\lambda_x f_x}{\lambda_h f}+\frac{f_l}{\lambda_h f})/\partial\tau)=\text{sign}(\frac{\partial A}{\partial\tau})>0$:

$$\frac{\partial(\frac{\lambda_x f_x}{\lambda_h f}+\frac{f_l}{\lambda_h f})}{\partial\tau}=\frac{f_x}{f}\frac{\frac{\partial\lambda_x}{\partial\tau}\lambda_h-\lambda_x\frac{\partial\lambda_h}{\partial\tau}}{\lambda_h^2}-\frac{f_l}{f}\frac{1}{\lambda_h^2}\frac{\partial\lambda_h}{\partial\tau}=\frac{f_x}{f\lambda_h}\frac{\partial\lambda_x}{\partial\tau}-\frac{1}{f\lambda_h^2}\frac{\partial\lambda_h}{\partial\tau}\left(\lambda_x f_x+f_l\right)>0$$

As suggested in the relative equilibrium cut-offs in equation (12), $\frac{\partial\lambda_x}{\partial\tau}<0$. The above inequality implies $\frac{\partial\lambda_h}{\partial\tau}<0$. The impacts of the trade cost reduction on the *ex post* fractions of the *low* technology firms (λ_l), of exporters (λ_x), and of the *high* technology firms (λ_h) are, respectively

$$\frac{\partial\lambda_l}{\partial\tau}>0;\ \frac{\partial\lambda_x}{\partial\tau}<0;\ \frac{\partial\lambda_h}{\partial\tau}<0$$

Finally, to determine the intra-industry effects of openness to trade on the equilibrium productivity cut-offs, recall the cut-offs solved in the proof of Proposition 3.2:

$$\varphi_l=\Psi\left\{f_l+\lambda_x f_x+\lambda_h f\right\}^{1/c}$$
$$\varphi_x=(\lambda_x)^{-1/c}\varphi_l=\Psi\left\{\frac{1}{\lambda_x}f_l+f_x+\frac{\lambda_h}{\lambda_x}f\right\}^{1/c}$$
$$\varphi_h=(\lambda_h)^{-1/c}\varphi_l=\Psi\left\{\frac{1}{\lambda_h}f_l+\frac{\lambda_x}{\lambda_h}f_x+f\right\}^{1/c}$$

where $\Psi\equiv(\frac{1}{\delta f_e}\frac{\sigma-1}{c-\sigma+1})^{1/c}$. The effects of the trade cost reduction on the productivity cut-offs are

$$\text{sign}\left(\frac{\partial\varphi_l}{\partial\tau}\right)=\text{sign}\left(\frac{\partial(\lambda_x f_x+\lambda_h f)}{\partial\tau}\right)<0$$

$$\text{sign}\left(\frac{\partial \varphi_x}{\partial \tau}\right) = \text{sign}\left(\frac{\partial(\frac{1}{\lambda_x} f_l + \frac{\lambda_h}{\lambda_x} f)}{\partial \tau}\right) > 0$$
$$\text{sign}\left(\frac{\partial \varphi_h}{\partial \tau}\right) = \text{sign}\left(\frac{\partial(\frac{1}{\lambda_h} f_l + \frac{\lambda_x}{\lambda_h} f_x)}{\partial \tau}\right) > 0$$

In sum, regardless of the factor-biased feature of technical change, $\frac{\partial \varphi_l}{\partial \tau} < 0$, $\frac{\partial \varphi_x}{\partial \tau} > 0$, and $\frac{\partial \varphi_h}{\partial \tau} > 0$. ■

Derivation of aggregate variables. With Pareto-distributed firm-level productivity, the productivity cut-offs are given as follows:

$$\varphi_l = \Psi \left\{f_l + \lambda_x f_x + \lambda_h f\right\}^{1/c}$$
$$\varphi_x = \Psi \left\{\frac{1}{\lambda_x} f_l + f_x + \frac{\lambda_h}{\lambda_x} f\right\}^{1/c} = \lambda_x^{-1/c} \varphi_l$$
$$\varphi_h = \Psi \left\{\frac{1}{\lambda_h} f_l + \frac{\lambda_x}{\lambda_h} f_x + f\right\}^{1/c} = \lambda_h^{-1/c} \varphi_l$$

where

$$\lambda_x = \left(\frac{\tau}{\Lambda}\right)^{-c} \left(\frac{f_x}{f_l}\right)^{\frac{c}{1-\sigma}}; \lambda_h = \left\{\left[\left(\frac{c_l}{c_h}\right)^{\sigma-1} - 1\right](1 + \tau^{1-\sigma}\Lambda)\frac{f_l}{f}\right\}^{\frac{c}{\sigma-1}};$$
$$r_{ld} = RP^{\sigma-1}\left(\frac{\rho}{c_l}\right)^{\sigma-1}$$
$$\Psi \equiv \left(\frac{1}{\delta f_e}\frac{\sigma-1}{\gamma}\right)^{1/c}; \Lambda = \frac{R^* P^{*\sigma-1}}{RP^{\sigma-1}}; \bar{\pi} = \frac{\delta P f_e}{1 - G(\varphi_l)}; \gamma \equiv c - \sigma + 1$$

The aggregate demand for emissions:

$$\begin{aligned}
\overline{E} &= M\left\{\int_{\varphi_l}^{\varphi_h} e_{ld}(\varphi)\mu(\varphi)d\varphi + \int_{\varphi_x}^{\varphi_h} e_{lx}(\varphi)\mu(\varphi)d\varphi \right.\\
&\quad \left. + \int_{\varphi_h}^{\infty} [e_{hd}(\varphi) + e_{hx}(\varphi)]\mu(\varphi)d\varphi\right\}\\
&= M\left\{\int_{\varphi_l}^{\varphi_h} \frac{\rho s_l^e}{p_e} r_{ld}(\varphi)\mu(\varphi)d\varphi + \int_{\varphi_x}^{\varphi_h} \frac{\rho s_l^e}{p_e} r_{lx}(\varphi)\mu(\varphi)d\varphi \right.\\
&\quad \left. + \int_{\varphi_h}^{\infty} \left[\frac{\rho s_h^e}{p_e} r_{hd}(\varphi) + \frac{\rho s_h^e}{p_e} r_{hx}(\varphi)\right]\mu(\varphi)d\varphi\right\}\\
&= M\frac{\rho r_{ld}}{p_e}\left\{s_l^e \int_{\varphi_l}^{\varphi_h} \varphi^{\sigma-1}\mu(\varphi)d\varphi + s_l^e \frac{r_{lx}}{r_{ld}} \int_{\varphi_x}^{\varphi_h} \varphi^{\sigma-1}\mu(\varphi)d\varphi \right.\\
&\quad \left. + s_h^e \left(\frac{r_{hd}}{r_{ld}} + \frac{r_{hx}}{r_{ld}}\right) \int_{\varphi_h}^{\infty} \varphi^{\sigma-1}\mu(\varphi)d\varphi\right\}\\
&= M\frac{\rho r_{ld}}{p_e}\left\{s_l^e \int_{\varphi_l}^{\varphi_h} \varphi^{\sigma-1}\mu(\varphi)d\varphi + s_l^e \Lambda \tau^{1-\sigma} \int_{\varphi_x}^{\varphi_h} \varphi^{\sigma-1}\mu(\varphi)d\varphi \right.
\end{aligned}$$

$$+s_h^e(1+\tau^{1-\sigma}\Lambda)\left(\frac{c_l}{c_h}\right)^{\sigma-1}\int_{\varphi_h}^{\infty}\varphi^{\sigma-1}\mu(\varphi)d\varphi\Bigg\}$$

$$=M\frac{r_{ld}\varphi_l^c}{p_e}\frac{c}{\gamma}\Bigg\{s_l^e(\varphi_l^{-\gamma}-\varphi_h^{-\gamma})+s_l^e\Lambda\tau^{1-\sigma}(\varphi_x^{-\gamma}-\varphi_h^{-\gamma})$$

$$+s_h^e(1+\tau^{1-\sigma}\Lambda)\left(\frac{c_l}{c_h}\right)^{\sigma-1}\varphi_h^{-\gamma}\Bigg\}$$

$$=M\frac{s_l^e r_{ld}\varphi_l^{\sigma-1}}{p_e}\frac{c}{\gamma}\left\{1+\Lambda\tau^{1-\sigma}\lambda_x^{\gamma/c}+(1+\Lambda\tau^{1-\sigma})\left[\frac{s_h^e}{s_l^e}\left(\frac{c_l}{c_h}\right)^{\sigma-1}-1\right]\lambda_h^{\gamma/c}\right\}$$

$$=M\frac{\sigma P f_l}{p_e}\frac{c}{\gamma}s_l^e\left\{1+\Lambda\tau^{1-\sigma}\lambda_x^{\gamma/c}+(1+\Lambda\tau^{1-\sigma})\left[\frac{s_h^e}{s_l^e}\left(\frac{c_l}{c_h}\right)^{\sigma-1}-1\right]\lambda_h^{\gamma/c}\right\}$$

Similarly, the aggregate demand for labor:

$$\overline{L}=M\left\{\int_{\varphi_l}^{\varphi_h}l_{ld}(\varphi)\mu(\varphi)d\varphi+\int_{\varphi_x}^{\varphi_h}l_{lx}(\varphi)\mu(\varphi)d\varphi+\int_{\varphi_h}^{\infty}[l_{hd}(\varphi)+l_{hx}(\varphi)]\mu(\varphi)d\varphi\right\}$$

$$=M\frac{\sigma P f_l}{w}\frac{c}{\gamma}s_l^l\left\{1+\Lambda\tau^{1-\sigma}\lambda_x^{\gamma/c}+(1+\Lambda\tau^{1-\sigma})\left[\frac{s_h^l}{s_l^l}\left(\frac{c_l}{c_h}\right)^{\sigma-1}-1\right]\lambda_h^{\gamma/c}\right\}$$

The aggregate expenditure on domestic and imported varieties:

$$R=\int_{\varphi_l}^{\varphi_h}r_{ld}(\varphi)M\mu(\varphi)d\varphi+\int_{\varphi_h}^{\infty}r_{hd}(\varphi)M\mu(\varphi)d\varphi+\int_{\varphi_x^*}^{\varphi_h^*}r_{lx}^*(\varphi)M^*\mu^*(\varphi)d\varphi$$

$$+\int_{\varphi_h^*}^{\infty}r_{hx}^*(\varphi)M^*\mu^*(\varphi)d\varphi$$

$$=M\sigma P f_d\frac{c}{\gamma}\left\{1+\left[\left(\frac{c_l}{c_h}\right)^{\sigma-1}-1\right]\lambda_h^{\gamma/c}\right\}$$

$$+M^*\Lambda^*\tau^{1-\sigma}\sigma P^* f_d^*\frac{c^*}{\gamma^*}\left\{\lambda_x^{*\gamma/c}+\left[\left(\frac{c_l^*}{c_h^*}\right)^{\sigma-1}-1\right]\lambda_h^{*\gamma/c}\right\}$$

With balanced trade condition where values of exports equal values of imports, the last equation is

$$R=Mr_{ld}\varphi_l^{\sigma-1}\frac{c}{\gamma}\left\{1+\left[\left(\frac{c_l}{c_h}\right)^{\sigma-1}-1\right]\lambda_h^{\gamma/c}\right\}$$

$$+Mr_{lx}\varphi_l^{\sigma-1}\frac{c}{\gamma}\left\{\lambda_x^{\gamma/c}+\left[\left(\frac{c_l}{c_h}\right)^{\sigma-1}-1\right]\lambda_h^{\gamma/c}\right\}$$

$$=M\sigma P f_l\frac{c}{\gamma}\left\{1+\Lambda\tau^{1-\sigma}\lambda_x^{\gamma/c}+(1+\Lambda\tau^{1-\sigma})\left[\left(\frac{c_l}{c_h}\right)^{\sigma-1}-1\right]\lambda_h^{\gamma/c}\right\}$$

The aggregate consumption on domestic and imported varieties:

$$\begin{aligned}
Q^{\rho} &= \int_{\varphi_l}^{\varphi_h} q_{ld}^{\rho}(\varphi)M\mu(\varphi)d\varphi + \int_{\varphi_h}^{\infty} q_{hd}^{\rho}(\varphi)M\mu(\varphi)d\varphi + \int_{\varphi_x^*}^{\varphi_h^*} q_{lx}^{*\rho}(\varphi)M^*\mu^*(\varphi)d\varphi \\
&\quad + \int_{\varphi_h^*}^{\infty} q_{hx}^{*\rho}(\varphi)M^*\mu^*(\varphi)d\varphi \\
&= M\left\{\int_{\varphi_l}^{\varphi_h}(RP^{\sigma-1})^{\rho}\left(\frac{\rho\varphi}{c_l}\right)^{\sigma-1}\mu(\varphi)d\varphi + \int_{\varphi_h}^{\infty}(RP^{\sigma-1})^{\rho}\left(\frac{\rho\varphi}{c_h}\right)^{\sigma-1}\mu(\varphi)d\varphi\right\} \\
&\quad + M^*\left\{\int_{\varphi_h^*}^{\varphi_x^*}(RP^{\sigma-1})^{\rho}\left(\frac{\rho\varphi}{\tau c_l^*}\right)^{\sigma-1}\mu^*(\varphi)d\varphi + \int_{\varphi_h^*}^{\infty}(RP^{\sigma-1})^{\rho}\left(\frac{\rho\varphi}{\tau c_h^*}\right)^{\sigma-1}\mu^*(\varphi)d\varphi\right\} \\
&= M(RP^{\sigma-1})^{\rho}\left(\frac{\rho\varphi_l}{c_l}\right)^{\sigma-1}\frac{c}{\gamma}\left\{1+\left[\left(\frac{c_l}{c_h}\right)^{\sigma-1}-1\right]\lambda_h^{\gamma/c}\right\} \\
&\quad + M^*(RP^{\sigma-1})^{\rho}\left(\frac{\rho\varphi_l^*}{\tau c_l^*}\right)^{\sigma-1}\frac{c^*}{\gamma^*}\left\{\lambda_x^{*\gamma/c}+\left[\left(\frac{c_l^*}{c_h^*}\right)^{\sigma-1}-1\right]\lambda_h^{*\gamma/c}\right\}
\end{aligned}$$

The first part of the last equation is the aggregate consumption on domestic varieties, while the second part denotes the aggregate consumption on imported varieties. The aggregate price index:

$$\begin{aligned}
P^{1-\sigma} &= \int_{\varphi_l}^{\varphi_h} p_{ld}^{1-\sigma}(\varphi)M\mu(\varphi)d\varphi + \int_{\varphi_h}^{\infty} p_{hd}^{1-\sigma}(\varphi)M\mu(\varphi)d\varphi \\
&\quad + \int_{\varphi_x^*}^{\varphi_h^*} p_{lx}^{*1-\sigma}(\varphi)M^*\mu^*(\varphi)d\varphi + \int_{\varphi_h^*}^{\infty} p_{hx}^{*1-\sigma}(\varphi)M^*\mu^*(\varphi)d\varphi \\
&= M\left\{\left(\frac{c_l}{\rho}\right)^{1-\sigma}\int_{\varphi_l}^{\varphi_h}\varphi^{\sigma-1}\mu(\varphi)d\varphi + \left(\frac{c_h}{\rho}\right)^{1-\sigma}\int_{\varphi_h}^{\infty}\varphi^{\sigma-1}\mu(\varphi)d\varphi\right\} \\
&\quad + M^*\left\{\left(\frac{\tau c_l^*}{\rho}\right)^{1-\sigma}\int_{\varphi_x^*}^{\varphi_h^*}\varphi^{\sigma-1}\mu^*(\varphi)d\varphi + \left(\frac{\tau c_h^*}{\rho}\right)^{1-\sigma}\int_{\varphi_h^*}^{\infty}\varphi^{\sigma-1}\mu^*(\varphi)d\varphi\right\} \\
&= M\left(\frac{\rho\varphi_l}{c_l}\right)^{\sigma-1}\frac{c}{\gamma}\left\{1+\left[\left(\frac{c_l}{c_h}\right)^{\sigma-1}-1\right]\lambda_h^{\gamma/c}\right\} \\
&\quad + M^*\left(\frac{\rho\varphi_l^*}{\tau c_l^*}\right)^{\sigma-1}\frac{c^*}{\gamma^*}\left\{\lambda_x^{*\gamma/c}+\left[\left(\frac{c_l^*}{c_h^*}\right)^{\sigma-1}-1\right]\lambda_h^{*\gamma/c}\right\}
\end{aligned}$$

As in Melitz (2003), one could easily derive that $Q = R/P$. ■