THE ENVIRONMENTAL EFFECTS OF TRADE WITHIN AND ACROSS SECTORS

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Abstract

This paper presents a model that combines within and across sector channels through which trade affects our environment by embedding heterogeneous firms and fixed costs into a two-sector framework with an endogenous response to environmental policy. In contrast to existing literature that tends to examine these channels separately, the combined framework developed here shows how cross-sector comparative advantage and within-sector responses to trade and environmental policy or factor endowments interact to affect our environment through three channels: changes in output, cross-sector market share, and emissions intensity. In contrast to a single-sector model with neutral productivity, consideration of two sectors allows for trade liberalization to affect the allocation of inputs in each sector and thereby affect total pollution output. The additional consideration of heterogeneous firm responses to falling trade costs will generate endogenous increases in productivity that increase output, reduce aggregate emissions intensity, and moderate the cross-sector resource adjustment, relative to a representative-firm model. Simulation results show how the combined framework can replicate existing empirical outcomes, and provide concise ceteris paribus insights regarding the potential role of trade and environmental policy changes and factor expansion in driving observed outcomes and their contribution to each of the three channels.

Keywords: Trade and Environment, Heckscher-Ohlin, Firm heterogeneity

JEL Classification: F11, F12, F18, F64, Q56, Q58

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1 Introduction

The past twenty-five years have given rise to a dramatic increase in globalization and trade which has been accompanied by a hot debate regarding the effects of trade liberalization on environmental outcomes.[1] Historically, studies investigating the effect of increased trade on the environment have focused on one of two channels. Early analysis focused on cross-sector comparative advantage. More recent investigation has explored the role of within-sector adjustments due to firm's heterogeneous responses to trade policy changes. This paper develops a model that brings these two approaches together, treating them as complementary rather than competing explanations, to provide insights into the complex ways that trade liberalization can drive environmental outcomes when the effects vary and interact within and across sectors.

To investigate the importance of these interactions this paper extends a two-sector trade and environment model, by incorporating heterogeneous firms and fixed costs. The resulting model, which I refer to as the "combined framework," incorporates elements from a trade and environment framework developed by Copeland and Taylor (2003) as well as a two-sector heterogeneous-firm model developed by Bernard et al. (2007b) in order to link firm-level decisions to aggregate environmental outcomes. The model provides a tractable framework in which to evaluate the complex effects of trade or environmental policy changes. In particular, the model shows how trade and environmental policy changes and differences in cross-country factor allocations influence both cross-sector resource movement, driven by a country's comparative advantage, and within-sector increases in productivity, driven by cross-firm competition and reallocation, which can interact to affect environmental outcomes.

The combined framework identifies environmental effects of a trade liberalization working, simultaneously, through three main channels identified in related literature: changes due to overall economic output (a scale effect), changes due to cross-sector shifts in economic activity (a composition effect), and changes in within-sector emissions intensity (a technique effect). Importantly, the model demonstrates how, in contrast to a representative-firm model, the heterogeneous responses of firms, as competition generates endogenous reallocation of resources towards more productive firms, can lead to productivity gains that spillover into reductions in aggregate emissions intensity and also reductions in the degree of cross-sector resource movement. Both of these effects serve to dampen emissions increases for countries holding a comparative advantage in emissions intense production, even when the relative stringency of environmental policy is unchanged.

[1] Cherniwchan et al. (2017) provide a comprehensive overview of recent work as well as discussion of potential future research avenues in this area.

Long-running concern regarding the environmental effects of trade has generally been divided into two areas: that trade liberalization would drive pollution to lightly regulated countries (a pollution haven hypothesis), and an alternative concern that pollution might concentrate in capital intense regions or countries (a factor-endowment hypothesis). While initial investigations of the pollution haven hypothesis found little evidence to support the hypothesis, more recent work using panel data, both within and across countries (see Greenstone (2002); Hanna (2004); Ederington et al. (2005); Levinson and Taylor (2008)), has found statistically significant evidence of these effects.[2] Work by Antweiler et al. (2001) emphasized that, by influencing costs of production, environmental regulation could affect a country's comparative advantage in addition to driving firms to increase abatement and lower their emissions intensity. Their work, and several related studies investigating the relative importance of the scale, composition, and technique channels using various decomposition methods (Levinson (2009); Grether et al. (2009); Levinson (2015); Brunel (2017); Shapiro and Walker (2017)) have generally identified a strong technique effect as the primary channel driving aggregate emissions reductions.[3] In addition, these studies have generally found that a trade-induced composition-effect appears to be of relatively little importance in explaining changes in total emissions.

While empirical decompositions of aggregate environmental trends have provided substantial evidence of the relative importance of both within and across sector channels in driving environmental outcomes, they tend to mask underlying micro-mechanisms that may influence one or both channels. In light of this concern Shapiro and Walker (2017) and Kreickemeier and Richter (2013) both develop models, investigating the environmental effects of trade, that incorporate heterogeneous firms, but abstract away from the cross-sector role endowments or environmental policy, and thus ignore the role of comparative advantage. Shapiro and Walker (2017) extend their model with significant empirical investigation but find little evidence of any environmental trade effect, arguing that the decline in U.S. manufacturing emissions they find is consistent with a doubling of environmental compliance costs from 1990-2008.

Other recent work, however, calls into question this conclusion–of a generally limited environmental effect of trade and, more specifically, a limited environmental role of cross-sector comparative advantage. For example, cross-country work by Frankel and Rose (2005)

[2] See Brunnermeier and Levinson (2004) for an overview of this literature.

[3] For example, Levinson (2009) decomposes a 27 percent observed decline in SO2 emissions among US manufacturers from 1987-2001 and finds that cross-sector composition changes are responsible for 24 percent of the gap between output and the actual decline in emissions, while within-sector technique changes are responsible for 76 percent. Shapiro and Walker (2017), using product-level data from 1990-2008, find that cross-sector composition changes are responsible for 37 percent of the gap between output and actual SO2 emissions, while within-sector technique changes are responsible for 63 percent.

finds that increased trade tends to reduce air pollution across several measured pollutants, while similar work by Managi et al. (2009) shows that these effects differ across developing and non-developing countries. Using plant-level data, Cherniwchan (2017) shows that trade liberalization embodied in NAFTA, and the following competitive response of firms, resulted in substantial within-plant reductions in emissions intensity that varied across industries, sufficient to explain two-thirds of the reductions via the technique effect documented by Levinson (2009). Barrows and Ollivier (2016) find that market forces working through cross-sector and cross-firm reallocation substantially reduce CO2 emissions and emissions intensity among Indian firms, even in the absence of direct environmental regulation. Their results indicate that composition effects are similar in magnitude to technique effects. Broner et al. (2012) make use of a 30 year panel covering 101 countries to uncover evidence that environmental regulation is an important, and causal, source of comparative advantage for countries. Additional firm-level studies show that exporting firms tend to exhibit lower emissions intensity (Holladay (2016); Forslid et al. (2015); Richter and Schiersch (2017)) and that trade liberalization drives down ambient pollution as firms respond to the market changes (Gutierrez and Teshima (2017)). Martin (2011), examining the environmental effects of falling trade barriers in India, finds that trade liberalization is associated with reallocation of output towards cleaner firms and substantial reduction in firm's emissions intensities, while Bombardini and Li (2016) find that recent trade liberalizations have led to increased emissions by exporting firms specializing in dirty sectors in China.

Together these studies indicate that trade liberalization can generate substantial environmental effects but that these effects vary by country, are influenced by environmental policy and other factors affecting cross-sector comparative advantage, and that the heterogeneous responses of firms to trade liberalization can generate substantial environmental effects.

This empirical evidence suggests a complex and nuanced role of trade in environmental outcomes and motivates the development of the combined framework. As in Bernard et al. (2007b), consideration of the asymmetric export opportunities afforded by comparative advantage in the current paper is key to understanding the implications of trade liberalization for environmental outcomes. As countries lower their trade barriers, the value of exporting rises and drives a competitive response among firms that drives an endogenous rise in productivity. This response is more pronounced in the comparative advantage industries because firms' export opportunities are greatest in those industries. With this asymmetric outcome at work across sectors, the combined framework yields several pertinent results.

First, in comparison to a representative-firm framework, where fixed technology and productivity parameters mean that a country's production possibility frontier is fixed, systematic reallocation of inputs and market share across firms that differ in their productivity levels will generate an endogenous rise in productivity. This productivity gain generates additional increases in output (a larger scale effect), endogenous decreases in emissions intensity (a technique effect) even when rigid environmental policy targets firms' emissions intensities, and a smaller composition effect. Work by Antweiler et al. (2001) and Cole and Elliott (2003) finds "surprisingly small" composition effects, relative to larger scale and technique effects associated with trade liberalization. In their approach, response to increased stringency of environmental policy, a within-firm reduction in emissions intensity, is the only mechanism driving the technique effect. The combined framework shows how the simultaneous consideration of endogenous reallocation of resources between firms may help to identify additional important environmental effects of a trade liberalization. In particular showing that even when trade may only induce a small composition effect (due to similarities in the trading partner's comparative advantage), trade liberalization still generates large scale and technique effects due to systematic reallocation of resources between heterogeneous firms.

Analytical approaches that attribute all reductions in aggregate emissions intensity (the environmental technique effect) to environmental regulation may miss reductions due to across-firm reallocation or within-firm technology upgrading motivated by trade policy changes and thus may be underestimating the environmental effects of trade policy. A similar point is highlighted by the findings of significant trade-induced within-plant reductions in emissions intensity by Cherniwchan (2017) and substantial cross-firm reallocation found by Barrows and Ollivier (2018), as well as the single-sector, heterogeneous-firm model developed by Kreickemeier and Richter (2013). However, trade-liberalization in single-sector models with neutral productivity–in which each firm's choice of relative factor shares depends on factor prices but not their specific productivity level–generally will not generate changes in factor allocations and usage, thus leaving total emissions unchanged as well.[4] In this case, similar to the key outcome in Melitz (2003), increased trade can lead to reallocation of factors to more productive firms and thereby to endogenous productivity growth, in turn raising output and lowering emissions intensity, but leaves total labor allocations and, thus total emissions, unchanged.[5] This leads to the second contribution of the combined framework.

By including multiple sectors and inputs, the combined framework admits a mechanism through which a trade-liberalization induces changes in a sector's factor usage, thereby leading to endogenous changes in total emissions driven by a country's comparative advantage.

[4]One alternative to this result can be found in Copeland and Taylor (2003) who develop a political economy model whereby trade liberalization leads to higher income and more stringent environmental regulation that lowers total emissions. Kreickemeier and Richter (2013) discuss trade-induced changes in total emissions that result when productivity is "strongly" emissions augmenting, rather than neutral.

[5]A similar result, in which total emissions are unaffected by trade liberalization, is obtained in Copeland and Taylor (2003) when examining a trade liberalization when the home country holds a comparative advantage in dirty production and environmental policy fixes total emissions through a permitting regime.

In addition, the combined framework shows that the interaction affects of cross-country comparative advantage with cross-firm reallocation rise with the country's comparative advantage. This is particularly relevant for the environmental composition effect, which is key to determining the sign of a trade liberalization's effect on the environment. In the combined framework, the heterogeneous responses of firms and resulting endogenous rise in productivity serves to moderate the movement of resources across sectors, thereby dampening the composition effect of trade and thus suggesting another challenge for empirical identification of this channel. Furthermore, in the combined framework, in contrast to the homogeneous firm approach of Copeland and Taylor (2003), aggregate productivity, and consequently a country's production possibilities frontier, is no longer fixed. By magnifying a country's output and moderating cross-sector resource movements, the combined framework shows that a country's trade-induced composition effect does not necessarily dominate the scale effect. Making inferences from a combined scale plus composition effect of trade may lead to incorrect conclusions about a country's comparative advantage and the environmental effects of trade.

Finally, the combined framework can be simulated, thus allowing for clear *ceteris paribus* insights into the environmental effects of various shocks to trade costs, environmental policy, or relative endowments. Taking parameter values from related literature, the simulation exercise shows that the combined framework is able to precisely recover the aggregate scale, composition, and technique effects estimated by Levinson (2009). The exercise also demonstrates how changes to trade and environmental policy, as well as changes to relative endowments, work together to influence each of the three effects. These results indicate that trade liberalization and increased environmental policy and relative expansion of factors, favoring relatively-clean production, are all required to obtain the actual outcomes estimated by Levinson (2009). This exercise further reveals that while trade liberalization is generating a relatively small composition effect, it is simultaneously driving significant output expansion, captured by the scale effect, and driving roughly one-third of the negative technique effect. In addition, when considering relative-factor expansion generating the observed composition effect, and the endogenous reductions in emissions intensity due to reallocation, the combined framework indicates that a simultaneous 20 percent increase in environmental stringency (measured by an implicit environmental tax) is needed to generate the observed reduction in emissions.[6]

The general equilibrium framework that generates these particular results provides a rich and also tractable setting for analyzing environmental implications of both trade and

[6]This contrasts with the approximately doubling of the environmental "tax" implied by Shapiro and Walker (2017).

environmental policy changes. Work by Romalis (2004) and Schott (2003) indicates that cross-country differences in factor allocation, as well as changes in factor expansion overtime continue to be important drivers of cross-country trade and production patterns. On the other hand, Bernard et al. (2007b) note that "recent research reveals that the poor empirical performance of neoclassical trade theory is driven by forces not captured in the standard Heckscher-Ohlin-Vanek model, including the existence of trade costs, factor price inequality, and variation in technology and productivity across countries." Two lines of existing research have shown that both across and within sector reallocation of resources are important channels influencing trade and output patterns. The omission of one or the other of these channels may be inhibiting investigation into the environmental effects of trade. The combined framework developed here brings these factors together, and highlights their importance for empirical investigation and policy evaluation.

The remainder of the paper is structured as follows. Section 2 develops the model. Section 3 describes firm and aggregate emissions demands and section 4 discusses integrated and free trade equilibria. Section 5 analyzes the environmental role of comparative advantage and trade, demonstrating how representative-firm results are nested in the combined framework. Section 6 presents the model under costly trade and compares the environmental effects of trade in a representative-firm model to those obtained in the combined framework. Section 7 presents related numerical results illustrating the evolution of various environmental effects for which closed-form solutions do not exist and also calibrates the model to replicate observed empirical outcomes. Section 8 concludes.

2 Setup

This section develops a two-sector, multi-input trade and environment framework with heterogeneous firms, fixed costs, and environmental policy under autarky, assuming trade costs are high enough to discourage any trade. The framework combines elements of Copeland and Taylor (2003) and Bernard et al. (2007b).

2.1 Demand

The domestic-only analysis provides the foundation that will apply to two trading partners, home and foreign or rest-of-world, $n \in \{H, F\}$, when the model is opened to trade. Countries are home to a continuum of heterogeneous firms each of which produces a differentiated variety in one of two sectors, $s \in \{1, 2\}$.[7] Firms produce with capital and labor. To discuss the model when opened up to trade, assume that the home country is capital abundant relative to the foreign country, so that $\bar{K}^H/\bar{L}^H > \bar{K}^F/\bar{L}^F$, where bars indicate each country's endowments.[8] To simplify notation, the analysis omits country indices where appropriate. Consumers enjoy consumption, C, of differentiated varieties, $\omega \in \Omega$, produced in both sectors. For simplicity assume consumer utility to be aggregated across sectors in a Cobb-Douglas fashion:

$$\underset{C_1,C_2}{U} = C_1^{\eta_1} C_2^{\eta_2}, \qquad \eta_1 + \eta_2 = 1, \quad \eta_1 = \eta \tag{1}$$

Consumption and a corresponding price index in each sector are both defined over varieties in a standard CES form:

$$C_s = \left[\int\limits_{\omega \in \Omega} q_s(\omega)^\rho \, \mathrm{d}\omega \right]^{\frac{1}{\rho}}, \qquad P_s = \left[\int\limits_{\omega \in \Omega} p_s(\omega)^{1-\sigma} \, \mathrm{d}\omega \right]^{\frac{1}{1-\sigma}} \tag{2}$$

where $\sigma > 1$ captures consumers' elasticity of substitution between varieties, and $\rho \equiv (\sigma - 1)/\sigma$. Using the consumer utility and price index defined above, consumer inverse demands for individual varieties in a given sector are given by:

$$q_s(\omega) = \eta_s R P_s^{\sigma-1} p_s(\omega)^{-\sigma} \tag{3}$$

where R represents aggregate expenditure, of which η_s represents the share of their income that consumers spend in sector s. Thus, $\eta_s R = R_s$ can be used interchangeably, where R_s is simply total sector revenue.

2.2 Production

The production setup draws on Copeland and Taylor (2003), the important difference being that the combined framework relaxes their assumption that firms are homogeneous with respect to their productivity levels.[9] A firm's gross or potential output, y, is produced with

[7] To focus on the comparative advantage role of relative factor endowments or environmental stringency, this analysis assumes that the two trading partners have the same technology.

[8] Throughout the model, capital letters will denote aggregate variables, while lowercase letters will denote firm-level variables.

[9] The modeling approach is also quite similar to the single-sector heterogeneous-firm model developed by Konishi and Tarui (2015), but with the addition of a second sector and an additional factor of production, capital.

a constant returns to scale technology and requires capital and labor:

$$y_s(\varphi,\, k,\, l) = \varphi l^{1-\beta_s} k^{\beta_s} \nu_s \tag{4}$$

where the productivity parameter, φ, is firm-specific and $\nu_s = \beta_s^{-\beta_s}(1-\beta_s)^{(\beta_s-1)}$. Additionally, production may result in a firm releasing emissions. Firms have access to an emissions-reducing abatement technology that exhibits decreasing returns. Similarly to Copeland and Taylor (2003), though with the addition of a firm-specific productivity component, I assume a specific abatement function, and emissions released per-unit of gross output, Λ_s, given by:

$$\Lambda_s(\theta_s) \equiv \frac{(1-\theta_s)^{\frac{1}{\alpha_s}}}{\varphi} \tag{5}$$

where $0 < \alpha_s < 1$ for a polluting sector. A lower α_s represents an increase in the cost effectiveness or efficiency of available abatement technology or a lower per-unit emissions requirement for a firm in a given sector. The variable $0 \leq \theta_s \leq 1$ represents the share of a firm's resources that they choose to devote to abatement. A firm may choose to reallocate some of their resources to increase their investment in abatement, for example if emissions are taxed, to reduce their emissions intensity. For the same investment in abatement, more productive firms will generate less emissions per unit produced.

Using (5) the net-output of a firm in a given sector, q_s (net of the share of resources devoted to abatement), can be written equivalently as a function of capital and labor inputs and the firm's abatement share choice, θ_s, or as a function of three inputs: capital, labor, and emissions, z.

$$\begin{aligned} q_s &\equiv (1-\theta_s) y_s(\cdot) \\ q_s &= \varphi z_s^{\alpha_s} (k_s^{\beta_s} l_s^{1-\beta_s})^{1-\alpha_s} \quad , \quad 1 > \beta_1 > \beta_2 > 0 \end{aligned} \tag{6}$$

As in Copeland and Taylor (2003), this specification is valid for $z_s \leq k_s^{\beta_s} l_s^{1-\beta_s}$, because $1 \geq \theta_s \geq 0$. If a firm chooses not to abate, and $\theta_s = 0$, their emissions will be proportional to their labor and capital inputs, net-output will equal gross-output, and each unit of output will generate one unit of pollution.[10]

Consistent with recent empirical literature, I assume that sector 1 is capital intense and emissions intense relative to sector 2.[11] To simplify the following analysis I assume that only

[10] As with any constant-returns to scale production function with neutral technology, this will mean that a firm's relative factor demands are not a function of their specific productivity level. Relative to another firm, however, any given firm's total demand for labor, capital, or emissions will vary, depending on their relative productivity levels.

[11] See Kahn (1999); Cole et al. (2005); Cole and Elliott (2005)

firms in sector 1 emit pollution (i.e. $\alpha_2 = 0$).

2.2.1 Cost Minimization

Following the literature on heterogeneous firms I assume that production also requires a fixed overhead investment that must be covered in each period, f_s, and has the same unit input requirements as variable production. The cost minimizing input bundle involves a choice regarding the amount of capital and labor that a firm will devote to output relative to the amount they will devote to abatement, which in turn implies a choice of how much emissions to generate relative to capital and labor. A given firm's cost-minimizing choices of k, l, and z in the net-output setup from (6) yields the following production cost function:

$$\Gamma_s \quad = \quad \left(\frac{q_s}{\varphi} + f_s\right) \frac{w^{1-\beta_s} i^{\beta_s}}{(1-\alpha_s)(1-\theta_s)} \tag{7}$$

where w and i capture wages and rents. A firm's optimal choice of abatement share, θ_s, is the cost-minimizing solution to their choice concerning the amount of capital and labor to devote to net output relative to the amount to devote to abatement:[12]

$$(1-\theta_s) = \left(\frac{w^{1-\beta_s} i^{\beta_s}}{t} \frac{\alpha_s}{1-\alpha_s}\right)^{\alpha_s} \tag{8}$$

where t represent a per-unit-of-emissions tax that is given exogenously.[13]

When environmental policy is less stringent, firms may chooses not to devote any of their capital and labor resources to investments in abatement.[14] Combining equations (6) and (8), as the relative stringency of regulation rises, represented by t, firms devote more resources to abatement, and net output falls. In the extreme, as θ_s approaches one, net-output (and consequently revenue), approaches zero, and the firm will exit the market. The following analysis focuses on the case when the emissions tax is high enough that firms choose to invest in some abatement, but low enough to allow some firms to continue in the market. Finally, it is worth noting that firms within the same industry do not differ in their optimal choice of

[12]Formally, the firm solves: $cost^{q_s}(w, i, t) = \min_{z_s, y_s} \{t \cdot z_s + cost^{y_s} \cdot y_s \, : \, (\varphi z)^{\alpha_s} y_s^{1-\alpha_s} = 1\}$.

[13]For simplicity, the current model abstracts away from the political-economy model that generates emissions taxes, though allowing for endogenous policy determination is feasible (see Copeland and Taylor (2003)). As discussed by Copeland and Taylor (2003), this framework can accommodate several forms of environmental policy. In addition to a fixed "tax," a rigid policy could target firms' emissions intensities, a common form of regulation (e.g. substantial portions of the U.S. Clean Air Act). When the tax is held fixed, changes in factor returns will in turn lead to changes in firms' abatement decisions and emissions intensity. When emissions intensities, θ_s, are the target, the "tax" implicitly adjusts to changes in factor returns.

[14]Under the simplifying assumption that sector 2 does not pollute, and $\alpha_2 = 0$, firms in sector 2 will not need to abate, and θ_2 will equal zero.

abatement share, since $(1 - \theta_s)$ is independent of individual productivity, and thus a firm's choice of emissions relative to their capital and labor inputs is only a function of technology parameters and relative factor prices. This also means that while firm's emissions intensity is inversely related to their productivity, the firm's total emissions will be directly proportional to the inputs hired and the sector's technology. This modeling approach is consistent with within-sector plant-level analysis by Shadbegian and Gray (2005) who "find little evidence that different subgroups of plants within an industry [based on differences in their production technology or by their choice between change-in-production- process (CIPP) and end-of-line abatement investment] have sizable differences in their production functions" (p 207).[15]

2.2.2 Profits and Pricing

The market is characterized by monopolistic competition. Firms wishing to enter the market and begin producing must sink a sector-specific fixed entry cost, f_{es}, which I assume has the same unit input requirement as the fixed production cost, and draw a unique productivity level from the distribution $G(\varphi)$. Due to this requirement, and the CES demand structure combined with the presence of fixed production costs, each variety will be produced by a single firm (and each firm will produce a single variety), and thus both firms and varieties can be indexed by their productivity level, φ.

In a monopolistically competitive market where consumers love variety, firms have some power to set prices above their marginal cost[16] and profit maximization yields the following price-setting rule:

$$p_s(\varphi) = \frac{w^{1-\beta_s} i^{\beta_s}}{(1-\theta_s)(1-\alpha_s)\rho\varphi} \tag{9}$$

where a firm's optimal price is merely a constant markup, ρ, over its marginal cost. This is the price the producer receives after paying emissions taxes and abatement costs.[17]

[15]This is in contrast to the single sector models that define firm's emissions per unit of labor solely as a declining function of the firm's productivity level (e.g. Kreickemeier and Richter (2013) and Tang et al. (2014)). This also contrasts slightly with the modeling choice made by Shapiro and Walker (2017) who incorporate a response to regulation, but model firm's abatement investment intensity as a function of their specific productivity level.

[16]As demonstrated in Baldwin et al. (2005) p. 40 when the number of firms/varieties grows large (approaching infinity), consumers' price elasticity of substitution equals σ whether firms are competing on price or on quantity and firms can be thought of equivalently as choosing prices or quantities.

[17]When firms are identical ($\varphi = 1$) and the elasticity of substitution between varieties is infinite, this pricing rule is identical to the "net producer price" developed by Copeland and Taylor (2003).

Combining this pricing rule with consumer's inverse demands from (3), and total costs from (7), a firm's revenue and profits can be written as:

$$
\begin{aligned}
r_s(\varphi) &= \eta_s R P_s^{\sigma-1} p_{sd}(\varphi)^{1-\sigma} \\
\pi_s(\varphi) &= \frac{r_s(\varphi)}{\sigma} - f_s \frac{w^{1-\beta_s} i^{\beta_s}}{(1-\alpha_s)(1-\theta_s)}
\end{aligned} \tag{10}
$$

where a firm's profits are revenue scaled by the elasticity of substitution, minus fixed costs. The firm's pricing rule implies that the relative revenue of two firms within the same sector and market and with access to the same abatement technology depends solely on their relative productivity: $r(\varphi^{'})/r(\varphi^{''}) = \left(\varphi^{'}/\varphi^{''}\right)^{(\sigma-1)}$.

A zero-profit condition identifies the productivity cut-off, φ_s^*, in each sector:

$$
r_s(\varphi_s^*) = \sigma f_s \frac{w^{1-\beta_s} i^{\beta_s}}{(1-\alpha_s)(1-\theta_s)} \tag{11}
$$

the difference from Bernard et al. (2007b) being the additional consideration of the firm's abatement choice, θ_s, that now affects firms' revenue calculation. Any firm drawing a productivity below the cut-off will not enter or operate. The existence of this productivity cut-off, generated by the presence of fixed overhead costs, is the first key aspect that is absent homogeneous-firm models investigating the role of trade on the environment. When combined with a distribution of firm productivity, the need to cover fixed costs means that only a subset of firms will select into the market.

Equilibrium in each market implies that average revenue and profits are equal to the revenue and profits of a firm with an average productivity draw: $\overline{r}_s = r_s(\tilde{\varphi}_s)$ and $\bar{\pi}_s = \pi_s(\tilde{\varphi}_s)$. Average productivity in a sector, $\tilde{\varphi}_s$, is an output-weighted average across all firms that draw a productivity above the zero-profit cut-off. This average is monotonically increasing in the productivity cut-off, φ_s^*, and captures the means by which endogenous changes in the productivity cut-off affect output, revenue, prices, and profits. This average can be used to rewrite the aggregate price index and output level, under autarky, for a given sector from (2) and (3) as:[18]

$$
\begin{aligned}
P_s &= M_s^{\frac{1}{1-\sigma}} p(\tilde{\varphi}_s) \\
Q_s &= M_s^{\frac{1}{\rho}} q_s(\tilde{\varphi}_s)
\end{aligned} \tag{12}
$$

where the aggregate values are defined across firms that are actually present in the market

[18]See Appendix A for average productivity definition and additional discussion.

sector via $\tilde{\varphi}_s$, and M_s is the mass of firms[19] operating in a given sector.

2.2.3 Free Entry

As in related heterogeneous-firm trade literature (see Bernard et al. (2007b) and Melitz (2003)), firms entering the market must cover a separate fixed cost of entry, f_{es}, and then face the continuous, exogenous, potential of a negative economic shock that forces them to shutdown if revenues are driven below the zero-profit cut-off level. The expected value of entry for a firm in a particular sector depends on the probability of successful entry, and the expected profits in the sector. Firms will continue to enter the market until the expected benefit of entry reaches zero. The combination of the free-entry condition and the zero-profit condition creates a series of two equations linking φ and $\bar{\pi}$ which identify φ_s^* as only a function of fixed costs and model parameters and completely pins down φ_s^* independent of factor rewards and other endogenous model variables.[20]

2.2.4 Factor Market Equilibria

Capital and labor that firms use for production and entry must clear their respective markets:

$$\begin{aligned} \bar{K} &= K_1 + K_2, \quad K_s = K_s^p + K_s^e \\ \bar{L} &= L_1 + L_2, \quad L_s = L_s^p + L_s^e \end{aligned} \tag{13}$$

where $\bar{K}$ and $\bar{L}$ denote the available supply of capital and labor (respectively), as determined by a country's factor endowments. The superscript p refers to factor demands for production, and the superscript e refers to entry requirements.

With a continuum of firms and products, and multiple sectors, the free entry and full employment conditions completely pin down factor prices according to the marginal productivity of the factors in the different sectors.[21]

3 Emissions Demand

To highlight the different contributions of the combined framework, I first analyze firm-level emissions demands and then aggregate those to analyze cross-sector demands.

[19]For expositional convenience the reader may refer to M_s as the number instead of mass of firms without loss of generality.

[20]See Appendix A.

[21]See Appendix B.

3.1 Firm-level Emissions

Using the firm profit function in (10), the unconditional demand for emissions emitted in the course of production by a firm in sector 1, denoted by the superscript p, is given by:

$$z_1^p(\varphi) \;=\; \left[\frac{q(\varphi)}{\varphi} + f_1\right](1-\theta_1)^{\frac{(1-\alpha_1)}{\alpha_1}} \tag{14}$$

where the first term in brackets captures what the firm spends on emissions generated in variable production of the consumption good, determined by demand for the variety based on consumer preferences, shown in equation (3).[22] The second term captures fixed environmental expenditures. Both of these features have known corollaries in current manufacturing practices. For example, continuous disposal, monitoring, reporting, and containment costs represent a marginal cost of emissions that firms face while investments in more efficient "control technology" for the express purpose of reducing emissions are other fixed environmental production costs that firms undertake–often to comply with environmental regulation and permit requirements–that provide services over time.[23]

Other things equal, a polluting firm's demand for emissions, z_1, decreases in response to more stringent emissions intensity targets (motivating increased investment in abatement, implied by an increase in the emissions tax, t, relative to the costs of capital and labor) or an increase in the efficiency of available abatement technology (i.e. α_1 falls). In addition, more productive firms will also demand more total emissions than less productive firms in the same industry and country. More productive firms are able to lower their prices and increase demand for their output which in turn leads them to employ additional factors of production, including emissions.[24] This does not imply, however, that industry-wide productivity gains contribute to higher emissions demand. To address the total impact of a policy change on emissions the model must also consider the reallocation effect as firms expand or contract as they increase their competition for resources–a margin that is absent in homogeneous-firm models. To address this general equilibrium channel, I turn now to aggregate emissions.

[22]This is nearly identical in form to the firm input-demands in Melitz (2003), with the additional consideration of multiple factor prices, captured in $(1-\theta_1)$.

[23]For example Heutel (2011) and Greenstone (2002) discuss the role that environmental policy plays in determining firms' investment in abatement equipment. They show that environmental policy can effectively serve as a barrier to entry or new investment, by raising the costs of these activities, correlating to fixed costs in the present model.

[24]Two firms in the same country and industry will demand equivalent environmental services for their fixed costs and the relative demands associated with variable production, v, will be determined solely by differences in the two firm's productivity levels: $z^v(\varphi')/z^v(\varphi'') = (q(\varphi')/\varphi')\,/\,(q(\varphi'')/\varphi'') = (\varphi'/\varphi'')^{(\sigma-1)}$.

3.2 Sector-level Emissions

Total emissions demand is the sum, across active firms, of total per-firm emissions due to production:

$$Z_1^p = \frac{1}{1 - G(\varphi_1^*)} \int_{\varphi_1^*}^{\infty} z_1(\varphi) M_1 g(\varphi) \mathrm{d}\varphi \tag{15}$$

plus emissions generated due to entry. Market clearing conditions then allow emissions demand in sector 1 to be written as a constant share of total sector revenue as:

$$Z_1 = Z_1^p + Z_1^e = \frac{\alpha_1 R_1}{t} \tag{16}$$

Given that $R_s = Q_s P_s$, and using (12) and the pricing rule from (9), aggregate emissions demand can be further decomposed into the mass of firms, average output, and endogenous average emissions intensity:

$$Z_1 = M_1 \bar{q}_1 \frac{(1-\theta_1)^{\frac{1-\alpha_1}{\alpha_1}}}{\tilde{\varphi}_1 \rho} \tag{17}$$

In the combined framework, total emissions are influenced by endogenous changes in average productivity and the mass of firms–margins that are absent in a homogeneous-firm framework–as well as endogenous changes to relative returns which in turn drive factor allocations across sectors and influence the mass of firms in each sector.

4 Autarky and Free Trade Equilibria

Merging techniques developed by Copeland and Taylor (2003) and Bernard et al. (2007b), it can be shown that a stable autarky equilibrium exists.[25] In addition, a free trade (no fixed or variable trade costs) equilibrium exists in which all firms produce for both the domestic and export markets. When countries have targeted the same emissions intensity (e.g. $\theta_1^H = \theta_1^F$), the free trade equilibrium can be explicitly characterized by factor price equalization (FPE).[26]

5 The Environmental Role of Comparative Advantage

This section discusses the environmental effects of trade, based on countries' comparative advantage differences, by evaluating the effects of a move from autarky to free trade. This

[25]See Appendix B.

[26]See Appendix B for additional discussion of the autarky and free trade equilibria.

step isolates the role of comparative advantage–whether flowing from a country's relative endowments or the relative stringency of their environmental policy–because in these two scenarios there is no differential selection into exporting by a sub-set of firms based on productivity differences. I analyze the environmental role of comparative advantage based trade in a regime of rigid environmental policy. Specifically, I assume that environmental regulation, in each country, targets firms' emissions intensity, θ_s. As in Copeland and Taylor (2003), when factor intensities are fixed, the combined framework inherits all of the comparative static properties of the Heckscher-Ohlin model of international trade, but now with additional margins of adjustment due to the inclusion of heterogeneous firms and fixed production costs. Since, from equation (8), θ_1 is a function of factor prices and an emissions "tax," an exogenous emissions intensity target implies that the implicit environmental tax adjusts to any changes in factor prices. This simplifies the analysis while also capturing a common approach to environmental policy.[27] This experiment highlights the environmental role of comparative advantage in the combined framework and serves as a benchmark case showing that the homogeneous-firm model is a special case of the combined framework. The opening of free trade leads relative output prices to converge, but in the absence of fixed costs of exporting, several key margins influencing the heterogeneous response of firms are left unchanged.

Proposition 1. *In the move from autarky to free trade, there is no change in the productivity cut-off, φ_s^*, or average productivity, $\tilde{\varphi}_s$, in any sector. If a country holds a comparative advantage in emissions-intense production–due to a relative abundance of capital or lower environmental stringency–the move from autarky to free trade raises emissions demand, while emissions demand falls if it holds a comparative advantage in clean production, ceteris paribus.*

Proof: See Appendix C.

Under autarky, the relative abundance of capital in the home country implies a lower relative return for capital.[28] If the two countries have equivalent environmental policies, then the relatively lower capital return also implies a relatively lower price for the capital intense good, and a comparative advantage in dirty production. Differences in the stringency of environmental regulation in the two countries could also influence their comparative advantage as more stringent regulation would serve to both raise average prices and lower the

[27] Examples of this type of emissions intensity target, along with several countries implementing such a policy regime, are discussed in Holland (2012) and Fischer and Springborn (2011).

[28] See appendix B for further discussion. As can be seen in equation (4), firm's gross output, and consequently their cost minimizing relative demand of capital to labor, is not influenced by environmental policy, though their net-output (6) and total factor demands are a function of the prevailing regulatory regime.

number of firms operating in the sector, which together would raise the prices in sector 1 and dampen and even eliminate a comparative advantage in the polluting sector.[29] Thus, the home country holds a comparative advantage in dirty production as long as higher costs imposed by environmental regulation do not reverse the relationship between relative output prices for the trading partners. In the move from autarky to free trade, relative output prices equalize and, when environmental regulation targets fixed emissions intensities, changes in relative output prices result in changes to factor prices. If the home country holds a comparative advantage in dirty production the relative price of sector 1 output rises along with the relative capital return. If, the home country, instead, holds a comparative advantage in clean production (for example, due to substantially more stringent environmental policy), the move from autarky to free trade results in a rise in the relative price of sector 2 output, and a decline in the relative capital return. The following discussion proceeds under the assumption that the environmental policy, at home, does not reverse the comparative advantage implied by the country's relative abundance of capital.

In the combined framework the fact that the move from autarky to free trade leaves the sector cut-off productivity unchanged arises because all firms are affected in a similar manner. All firms are subject to foreign competition and all gain access to the foreign market and will select into exporting. Although the switch to free trade does affect relative factor returns, the absence of fixed trade costs means that incumbent firms are able to pass any changes in input costs along to consumers as marked up prices. With identical factor intensities for production and entry, the changes to the cost of production and value of entry are symmetric, leaving the productivity cut-offs unchanged.[30]

To evaluate the role that trade plays in determining emissions demand, given in (16) and (17), first consider the effect on average firm output, given by $q_s(\tilde{\varphi}_s) = (\tilde{\varphi}_s/\varphi_s^*)^{\sigma}\, q_s^* = (\tilde{\varphi}_s/\varphi_s^*)^{\sigma}\, (\sigma - 1) f_s \varphi_s^*$.[31] Average firm output is pinned down by the productivity cut-off, and is therefore unchanged. Thus, in the absence of a change to the productivity cut-off and average productivity or firms' abatement investment share, falling trade costs only influence

[29] Copeland and Taylor (2003) make a similar point by distinguish between a "Pollution Haven Effect" and the stronger "Pollution Haven Hypothesis" and noting that a country's comparative advantage in relatively clean production, due to relative labor abundance, could still be moderated by less stringent environmental policy.

[30] As in Melitz (2003), this result is due to the combination of CES preferences and the assumption that firms use the same factor intensity for fixed and variable production.

[31] Under free trade, compared to autarky, firms offer their products in both the domestic and export markets. Under free trade, all operating firms also export and average revenue is merely given by $\bar{r}_s = [\bar{r}_{sd} + \bar{r}_{sx}]$. In the absence of trade costs, the domestic and export prices are equivalent, and average output is given by $\bar{q}_s = \bar{r}_s/\bar{p}_s = [\bar{q}_{sd} + \bar{q}_{sx}]$. Furthermore, $q_s(\tilde{\varphi}_s)/q_s(\varphi_s^*) = (\tilde{\varphi}_s/\varphi_s^*)^{\sigma}$ and from the zero-profit entry cut-off (11), $q_s(\varphi^*) = (\sigma - 1) f_s \varphi_s^*$. See appendix C for further discussion of the autarky and free trade equilibria.

a country's emissions demand through changes in the mass of firms, given by

$$M_s = \frac{R_s}{\bar{r}_s} \tag{18}$$

In the move from autarky to free trade, changes in the mass of firms are associated with relative output changes as resources shift between sectors according to the country's comparative advantage. Capital and labor move into the comparative advantage dirty sector at home and revenue, R_1, rises while revenues decline in the disadvantaged sector. From equation (16), this leads to an increase in emissions demand in the home country and a decline in the foreign. In the combined framework, other things equal, this corresponds to an increase in the mass of firms and varieties, M_1, in the dirty sector.

Proposition 1 highlights how differences in environmental policy and factor endowments influence emissions demand in this general equilibrium framework by affecting a country's comparative advantage. The benchmark case–moving from autarky to a free trade regime in which all firms export–essentially mirrors the costly trade insights of the representative-firm model developed by Copeland and Taylor (2003), relating trade to cross-sector resource movements and changes in emissions demand, but with the added insight that cross-sector movement of resources into the comparative advantage sector, induced by relative wage adjustments, work through firms' heterogeneous responses driving changes in the relative mass of firms in each sector.

6 Costly Trade

The free trade scenario, analyzed in the previous section, omits both fixed and variable trade costs. However, fixed trade costs are known to be an important factor influencing firms' decision of whether or not to export,[32] and their inclusion in the model generates an additional cut-off that serves to bar some operating firms from profitably entering into export markets, which is a prevalent feature of international trade data.[33] I turn now to analyze the model under the assumption of costly trade.

This section re-introduces notation for home and foreign variables when necessary, and distinguish between domestic and export values. While trade costs come in many forms, I follow the broader trade literature in assuming that firms face both a fixed cost of exporting,

[32] See Roberts and Tybout (1997a,b) for examples of the importance of fixed export costs determining firms' export decision.

[33] For example Bernard et al. (2007a) present broad evidence that only a subset of firms export, even in narrowly defined industries.

[34] as well as variable trade costs summarized by a standard "iceberg" form in which a share, $\tau_s > 1$, of the good must be shipped in order for a whole unit to reach the destination. Under such a regime, export prices (p_{sx}) are a markup over domestic prices (p_{sd}) given by:

$$p_{sx}^n(\varphi) = \tau_s p_{sd}^n(\varphi) = \frac{\tau_s (w^n)^{1-\beta_s} (i^n)^{\beta_s}}{(1-\theta_s^n)(1-\alpha_s)\varphi\rho} \quad , \qquad \text{for } n \in \{H,\ F\} \tag{19}$$

Under costly trade, price indices vary across countries due to differences in the mass of firms, factor price differences, different variety prices charged in home versus export markets (due to variable trade costs), and differences in the number of exporters versus domestic-only producers (due to entry barriers presented by fixed and variable trade costs). In addition, the costly trade price index in each sector is a function of the prices of both the mass of varieties produced domestically as well as the varieties available for import.[35] Compared to autarky, exporting now presents a new potential revenue and profit opportunity for firms, and exporting firms in the home country receive additional revenue and profits from exporting given by the export corollary to (10):

$$\begin{aligned} r_{sx}^H(\varphi) &= \tau_s^{1-\sigma} \left(\frac{P_s^F}{P_s^H}\right)^{\sigma-1} \left(\frac{R^F}{R^H}\right) r_{sd}^H(\varphi) \\ \pi_{sx}^H(\varphi) &= \frac{r_{sx}^H(\varphi)}{\sigma} - f_{sx} \frac{(w^H)^{1-\beta_s}(i^H)^{\beta_s}}{(1-\theta_s^H)(1-\alpha_s)} \end{aligned} \tag{20}$$

Since market entry costs are sunk, any firm with a productivity high enough to allow them to profitably export will also serve the domestic market, thus an exporting firm earns revenues and profits from domestic sales (given in (10)) plus revenue and profit from exporting.

As can be seen in the export profit equation, exporter's additional fixed exporting cost, f_{sx}, results in an additional productivity cut-off for entry into the export market following from the zero-export-profit condition:

$$r_{sx}(\varphi_{sx}^*) = \sigma f_{sx} \frac{(w^H)^{1-\beta_s}(i^H)^{\beta_s}}{(1-\theta_s^H)(1-\alpha_s)} \tag{21}$$

The export cut-off can then be related to the market entry cut-off in (11) by:

$$\varphi_{sx}^{*H} = \tau_s \left(\frac{P_s^F}{P_s^H}\right) \left(\frac{R^F}{R^H}\frac{f_{sx}}{f_s}\right)^{\frac{1}{\sigma-1}} \varphi_s^{*H} \tag{22}$$

[34] This can be thought of as capturing the costs involved with developing distribution networks in a foreign country, researching and complying with foreign regulations, etc.

[35] See Appendix B, (B.19), for further discussion of the costly trade price indices.

The introduction of fixed and variable trade costs results in market segmentation, according to productivity. Firms that draw a productivity above the entry cut-off enter and serve the domestic market as under autarky. Of those, a share will draw a productivity level high enough to allow them to also enter the export market.

6.1 Free Entry

As in the autarky or free trade cases, firms will choose to enter the market if they expect to earn revenues sufficient to cover the costs of entry. Under costly trade, firms have the additional consideration of potential profits to be earned in the export market, if their productivity draw is sufficiently high to allow them to profitably cover the additional fixed costs associated with serving a foreign market. Similarly to the autarky or free trade cases, the free-entry condition can be written as a function of parameters and productivity cut-offs. As in Bernard et al. (2007b), the expected value of entry is determined by the expected value of entering and serving the domestic market, plus a positive term capturing the expected value of entering and serving the foreign market.[36] Thus, as in the free trade and autarky cases, value of entry is monotonically decreasing in the productivity cut-off, φ_s^*. As the value of entry into the export market in a sector rises, firms will seek to enter the sector. The additional competitive activity of this trade liberalization will drive the productivity cut-off higher, which in-turn lowers the expected value of entry until a costly trade equilibrium value is reached.

6.2 Costly Trade Equilibrium

Building on work by Bernard et al. (2007b) with the inclusion of an emissions input and environmental regulation, it can be shown that a stable equilibrium exists in both factor and output markets under costly trade.[37] The costly trade equilibrium in the combined framework provides the foundation for the following analysis and related numerical exercises regarding the role of trade policy in determining environmental outcomes and allows for straightforward comparison of the predictions to those obtained in representative-firm models.

6.3 Prices and Productivity in the Costly Trade Equilibrium

Many conclusions drawn by Bernard et al. (2007b) regarding factor returns, factor allocation, and welfare continue to hold with the addition of an emissions component in production and

[36] See Free Entry under costly trade discussion in Appendix B for further details.

[37] See Appendix B.

accompanying environmental regulation. As in Melitz (2003), opening up a country to trade will generate a rise in productivity as firms compete for inputs as they vie for entry into the foreign market. One of the key insights derived by Bernard et al. (2007b) by embedding heterogeneous firms in a model of comparative advantage is that these productivity gains will be correlated with the country's comparative advantage, and the productivity cut-off and average productivity will rise by more in the comparative advantage sector and contribute to a decline in prices. However, as in the standard two-inputs, two-sector Heckscher-Ohlin trade model, there are additional competing effects that make analytically signing the total change in prices impossible.

In particular, under costly trade, a reduction in trade costs generates four important affects that influence output prices in each sector: (1) an increase in the relative reward of the abundant factor, (2) a rise in the productivity cut-offs and average productivity in both sectors which lowers prices, (3) increased competition for domestic inputs among firms leading to firm exit and fewer domestic varieties, which puts upward pressure on prices, and (4) an increase consumers access to foreign varieties, further lowering prices. Proofs and intuition for these effects in the combined framework are identical to the discussion in Bernard et al. (2007b).[38] As in Copeland and Taylor (2003), the introduction of environmental regulation raises the costs for the polluting sector and thus influences prices and the country's comparative advantage. Following their approach, emissions can be modeled as an additional factor with an associated factor cost. As shown by Copeland and Taylor (2003), the standard Heckscher-Ohlin and Stolper-Samuelson results are straightforward to obtain when countries pursue a rigid environmental policy, e.g. targeting firm emissions intensity, θ_s. In addition, regarding the latter three effects, the inclusion of environmental regulation does not change the conclusions drawn regarding the affect of trade liberalization on productivity, shown by Bernard et al. (2007b), since the productivity cut-off is not influenced by factor costs, including environmental regulation.

The first effect, relating relative price changes to changes in relative factor rewards, is the standard Stolper-Samuelson result of a two-input, two-sector, representative-firm trade model: as countries lower their trade costs, relative prices converge, leading to a rise in the value of country's comparative advantage sector and an increase in the relative return of the country's abundant factor. The latter three effects are introduced with the inclusion of heterogeneous firms. The combined effect of the latter two channels on the total mass of varieties available to consumers, and consumer welfare, is ambiguous.

I turn now to discuss, in more detail, how the interaction of heterogeneous-firms' responses with a country's comparative advantage affects emissions demand.

[38] See their *Proposition 7*.

6.4 The Combined Environmental Effects

When countries differ in their comparative advantage, and when fixed costs are a key barrier influencing firm's decision regarding whether or not to export, the environmental responses to trade liberalization within and across sectors will interact. Following related environmental literature, aggregate emissions demand from (16) can be decomposed into scale, composition, and technique effects, using the fact that $R_s = Q_s P_s$:

$$Z_1 = \underbrace{Q}_{\text{Scale}} \times \underbrace{\frac{Q_1}{Q_1 + Q_2}}_{\text{Composition}} \times \underbrace{\frac{\alpha_1 P_1}{t}}_{\text{Technique}} \tag{23}$$

where total output, the scale effect, is given by $Q = Q_1 + Q_2$. Under costly trade, the price index is a function of both domestic and foreign offerings in the sector.[39]

As written, the aggregate decomposition in equation (23) is identical to the decomposition used by Copeland and Taylor (2003).[40] In contrast to a homogeneous-firm framework, the scale, composition and technique channels are driven not only by specialization, relative-endowments, and environmental policy. In the combined framework these three channels are also influenced by the endogenous determination of average productivity. In turn, endogenous changes to average productivity in each sector influence the mass of firms and varieties and serve as an additional channel affecting prices, output, and emissions demand. In contrast to a single-sector model with heterogeneous-firms that produce using a single input and neutral technology, total inputs in a sector are not fixed, but can adjust by moving across sectors according to the country's comparative advantage. Implementing an abatement function like that used by Copeland and Taylor (2003) in which productivity does not affect a firm's choice of emissions relative to labor, total emissions are unaffected by changes in average productivity in the single-sector when firm's abatement choices are unchanged, since total factor employment remains unchanged in a single-sector framework.[41]

[39] The aggregate costly-trade price index is identical to the index derived by Bernard et al. (2007b). See the appendix and equation (B.19) for further details.

[40] See Copeland and Taylor (2003) equations (2.16), (7.8), and (7.14). The difference being that for Copeland and Taylor (2003), the price index under costly trade is only a trade-cost markup of the representative firm's marginal cost, whereas in the heterogeneous framework it is also a function of the distribution of operating firms at home and abroad, see equation (B.19).

[41] With the addition of emissions to a single-sector increasing-returns-to-scale model with heterogeneous-firms, like Melitz (2003), trade-liberalization-induced productivity gains generate scale and technique-type effects. There is no composition effect, since the entire economy is represented by the single sector ($Q_2 = 0$ and $Q_1 = Q$). Another way to see this, is to note, as in Melitz (2003), that total revenue is pinned down by factor allocations and factor returns (which are unchanged in a single-sector model, or, more generally, when relative prices across countries are identical and the country does not hold a comparative advantage. In this case, total emissions ($Z_1 = (\alpha_1 R_1)/t$) will also be unchanged. Changes to aggregate productivity, driving

Trade liberalization under costly trade induces multiple interactions between a country's comparative advantage and endogenous productivity gains that serve to affect aggregate emissions demand. In particular, the opening of costly trade generates a smaller increase in emissions demand for a country that holds a comparative advantage in emissions-intense production, by moderating cross-sector resource movements, compared to a homogeneous-firm model.

Proposition 2. *The opening of costly trade augments each of the traditional scale, composition, and technique effects, relative to the homogeneous-firm framework, in the following ways:*

(a) Other things equal, the increase in average productivity in the sector raises output and thus magnifies the increases in emissions demand via the scale effect.

(b) The increase in productivity raises average output, $q_s(\tilde{\varphi}_s)$, in all sectors. Other things equal, the largest increase occurs in the comparative advantaged sector and emissions demand rises via the composition effect if the emissions intense sector holds the comparative advantage.

(c) Other things equal, the increase in productivity lowers the relative mass of polluting firms putting downward pressure on emissions demand. This moderates, but does not reverse, the rise in emissions demand due to the forces of comparative advantage working through the composition effect.

(d) Other things equal, endogenous increases in productivity lowers emissions intensity and emissions demand, generating a negative technique effect, even when the relative cost imposed by environmental policy is fixed.

Proof: See Appendix C.

This proposition highlights several results, summarized by the point that correctly evaluating and understanding how trade affects the environment–working through the scale, composition, and technique effects–requires consideration of factors influencing cross-sector comparative advantage as well as heterogeneous firm response within-sectors.

reduction in aggregate output prices, will generate exactly off-setting effects via positive scale ($Q_1 = R_1/P_1$) and negative technique ($\alpha_1 P_1/t$) effects. This is also the result obtained under autarky for any shocks that generate changes in productivity but leave equilibrium factor prices and factor allocations unchanged. Kreickemeier and Richter (2013) make the same observation, discussing their single-sector model, but go on to show how endogenous productivity gains can reduce aggregate emissions under the assumption that productivity is "strongly" emissions-augmenting, which equates to larger more productive firms using less emissions per other inputs. As discussed above, the choice of abatement and productivity functions with a neutral effect of productivity, in setup of the present combined framework, is motivated by empirical work by Shadbegian and Gray (2005).

In a neoclassical homogeneous-firm model, increases in emissions demand via the scale effect are driven by specialization and corresponding output gains due to trade, or by scaling up the supply of inputs, holding sector output-shares and emissions intensities fixed. In the combined framework, when trade involves additional fixed investment costs, trade liberalization also stimulates competition among individual firms and average productivity rises as inputs are reallocated to more productive firms. This in turn serves to increase output and represents an additional channel that magnifies the traditional scale effect and increases national emissions.

Proposition 1 highlighted the role of relative factor abundance and relative environmental stringency in affecting a country's emissions demand as resources shift across sectors driven by relative price changes according to the country's comparative advantage. In the combined framework, the presence of fixed costs and heterogeneous firms induces two new channels also working through the composition effect. Following a reduction in trade barriers, the productivity cut-off rises as does average productivity in all sectors. This rise in average productivity translates to a rise in average output, $\bar{q}_s$, in both sectors. However, exporting is more attractive in the comparative advantage sector, due to the relative increase in its output price. As a result, the expected value of entry rises by more in the comparative advantaged sector, the free-entry productivity cut-off rises by more in that sector, and thus average output rises by more. Other things equal, the resulting increase in relative average output in the home country, $q_1(\tilde{\varphi}_1)/q_2(\tilde{\varphi}_2)$, raises relative sector output and thus emissions demand via the composition effect when the home country holds a comparative advantage in dirty output.

The mass of firms in a sector is given by $M_s = R_s/\bar{r}_s$. Due to the presence of trade costs, only a subset of operating firms will find it profitable to export. As trade barriers fall, the value of exporting rises and more productive firms increase their demand of inputs in order to serve the newly accessible foreign market. This increases the average size of firms that are able to remain and also raises real factor prices which, in turn, drives less productive firms from the market, lowering M_s. Again, this is larger in the comparative advantaged sector and thus reduces emissions demand via the composition effect, other things equal.

In contrast to a homogeneous-firm model, not all of the increased demand for output from a country's comparative advantaged sector must be produced by shifting resources across sectors. Instead, some of the output is made up by increased productivity–a channel that is absent from homogeneous frameworks.[42] However, as shown in *Proposition 1*, the net effect of a trade liberalization is to change the relative mass of firms according to the country's comparative advantage: M_1^n/M_2^n rises at home, but falls in the foreign country.

[42] A similar result regarding employment is highlighted by Bernard et al. (2007b).

While relative movement of resources across sectors, according to a country's comparative advantage, dominates the influence of changing productivity captured in the composition effect, in the combined framework this cross-sector effect due to comparative advantage is dampened by the presence of heterogeneous firms and the ensuing productivity gains that arise from a trade liberalization.

Finally, endogenous productivity gains directly influence aggregate emissions intensity, captured by the technique effect. In the homogeneous-firm framework developed by Copeland and Taylor (2003), per-unit emissions are only reduced following a trade liberalization if paired with an increase in the relative stringency of environmental regulation that induces firms to increase the share of resources devoted to abatement and thereby reduce their emissions intensity. In the combined framework, even if this channel is held fixed and environmental policy leaves emissions intensity unchanged at the firm level, endogenous competition for inputs reallocates resources towards more productive firms, resulting in the least productive and most emissions intense producers exiting the market. The rise in average productivity (which occurs in both sectors and countries) drives a decline in aggregate prices, other things equal, and directly reduces emissions intensity in the polluting sector.

Taken together, compared to a representative-firm framework the inclusion of heterogeneous firms and fixed costs magnifies the scale effect, moderates the composition effect, and generates a technique effect, even when environmental policy targets fixed emissions intensity.

Finally, the interactive heterogeneous responses of firms to a trade liberalization will vary from country-to-country depending on the strength of the country's comparative advantage.

Proposition 3. *The magnifying effect of endogenous productivity gains on the scale and technique effects and the moderating pressure on the composition effect rises with the country's comparative advantage.*

Proof: See Appendix C.

The primary insight that arises from the addition of heterogeneous firms, in comparison to a representative model, is the endogenous rise in the productivity cut-off and average productivity in each sector. As was first shown by Bernard et al. (2007b), this effect can be magnified in a multi-sector framework and is correlated with the country's comparative advantage.

In particular, as a country opens to trade, entry into the comparative advantage sector is relatively more attractive which drives up the productivity cut-off in the comparative advantage sector higher than in the other sector. This magnification effect, on the productivity cut-off, rises with a country's comparative advantage as larger differences in the relative abundance of endowments or environmental policies drive the relative autarky prices of the two countries apart. For a country with a comparative advantage in dirty production, while the rising productivity magnifies the scale effect, driving up emissions demand in the polluting sector, it also generates a reduction in emissions intensity and moderates the increase working through the cross-sector composition effect. Both of the latter effects serve to further reduce the rise in emissions, compared to a representative-firm model where productivity is fixed. Thus, while a representative firm predicts that trade liberalization raises emissions demand for a country holding a comparative advantage in emissions-intense production, the combined framework highlights that the simultaneous moderating effects of firm's heterogeneous responses are also rising with the strength of the comparative advantage effect.

In addition, by considering multiple sectors and inputs, the combined framework contrasts with single-sector approaches by maintaining a channel (cross-sector resource adjustments) through which trade leads to changes in total emissions in accordance with a country's comparative advantage.

Still, signing the combined environmental affect of trade working through each of three channels is prevented by simultaneous competing affects driving output prices in this multi-sector framework. The following section addresses this shortcoming by parameterizing the general equilibrium foundation of the model to simulate the aggregate environmental affects of trade liberalization in this combined framework.

7 Numerical Solutions

In this section I parameterize and solve the model, modifying an approach developed by Bernard et al. (2007b). The simulation exercise is comprised of three main parts: the first compares the environmental effects of trade liberalization obtained in the combined framework to those that would be obtained in both a single-sector model, and a two-sector homogeneous-firm model.[43] The second part further shows the ways in which a country's comparative advantage interacts with the endogenous determination of productivity. The third part of the exercise compares results obtained in the combined framework to the empirical estimates of the scale, composition, and technique effects presented by Levinson (2009).

To begin, I assume that all industry parameters, except factor intensities, are the same across sectors. I set sector 1 as the capital intense sector ($\beta_1 = 0.6$ and $\beta_2 = 0.4$) and assume

[43] This framework, which allows me to leave preferences and price indices unchanged in the comparison, is analogous to the imperfect-competition representative-firm model discussed in Helpman and Krugman (1985).

that $\alpha_1 = 0.011$, based on values of α estimated by Shapiro and Walker (2017). These technology parameters are assumed to be equal across counties. The difference between the combined framework and the homogeneous-firm model is the endogenous determination of productivity.

I assume an ex ante Pareto productivity distribution:

$$g(\varphi) = \frac{ak^a}{\varphi^{a+1}} \tag{24}$$

where k is the minimum possible value for productivity, and $a > 0$ is the distribution's shape parameter. I further assume that $a > \sigma - 1$. The Pareto distribution is widely used in related literature since it is both tractable while also providing a relatively good approximation of actual industry productivity distributions.[44] So that the two homogeneous and heterogeneous-firm models yield identical outcomes under autarky, I include both fixed and variable costs of production and exporting in both models. The first set of results compare the effects of a symmetric reduction in trade costs from 50 percent to 10 percent (i.e $\tau = 1.5$ to $\tau = 1.1$) on emissions demand in the home country.[45] Additional details of the simulation equations and parameter choices are discussed in the supplementary appendix.[46]

7.1 Environmental Effects of Heterogeneous Firms and Comparative Advantage

The first part of this exercise affords the ability to trace out the evolution of some aspects of emissions demand that cannot be explicitly characterized in theory due to interacting, and sometimes competing, channels operating in the transition between steady states, highlighted in *Propositions 1–3*. The results compare the scale, composition, and technique effects, as well as the overall environmental effect of trade obtained in the combined framework when the home country has a comparative advantage in clean and then dirty production. These results are then compared to those obtained in a heterogeneous-firm model in the absence of a comparative advantage (thus shutting down the trade-induced channel driving cross-sector resource movement), and then finally to results obtained in a homogeneous-firm, two-sector model, in which productivity is fixed, and firms produce a continuum of varieties.

[44]See Axtell (2001) and Helpman et al. (2004). The assumption that $a > \sigma - 1$ follows Bernard et al. (2007b) and ensures that the variance of log productivity is finite.

[45]The evolution of other key endogenous variables, aside from emissions demand, such as the productivity cut-off, probability of exporting, average firm output, relative and real wages, welfare, and the mass of firms all evolve similarly to the results laid out in Bernard et al. (2007b).

[46]The supplementary simulation appendix and related files can be found online in the Mendeley Data repository.

To focus on the role that endogenous entry and production choices by heterogeneous firms play in determining aggregate emissions outcomes, I initially set technology parameters, preferences, fixed costs, and environmental regulation (via an emissions intensity target, $\theta_1 = 0.035$) to be identical across countries.[47] The first case evaluates the environmental consequences of a trade liberalization for the home country when the foreign country is relatively capital abundant and holds a comparative advantage in dirty production.[48] In the second case, the endowments are reversed to show the outcome when the home country is capital abundant and thus holds a comparative advantage in dirty production. Taking logs and differentiating equation (23), the total percent-change in emissions is equal to the sum of the percent change in each of the scale, composition, and technique effects. Figure D.1 presents the trade-induced changes in environmental outcomes working through the three effects and is formatted as an index, with each channel set to 100 under Autarky, and then showing the percent-changes in emissions outcomes under costly trade as the variable trade-costs are adjusted.[49]

In the first panel of Figure D.1, when the home country has a relative abundance of capital (and, given the same environmental stringency, a comparative advantage in clean production), the combined framework shows that trade liberalization leads to an increase in output (scale: +17 percent), a shift of factors and market share towards the cleaner sector (composition: -16 percent),[50] and a reduction in emissions intensity in the polluting sector as resources are reallocated to more productive firms within the polluting sector (technique: -15 percent), even though the country is pursuing a rigid environmental policy by targeting firms' emissions intensities, θ_s. Taken together, these imply that trade liberalization for the home country is leading to a reduction in total emissions of 14 percent when holding a comparative advantage in clean production. In the second panel, the capital and labor endowments have been reversed. In this case, the combined framework shows the trade liberalization leading again to an increase in output (scale: +16 percent), but to a shift in factors and market share towards the dirty sector (composition: +13 percent), and, again,

[47]The model can be solved by setting emissions taxes, or targeting a specific firm-level emissions intensity (i.e. holding θ_s fixed). The conclusions in *Proposition 2* and the simulation results bear the same message under either policy regime, though the precise solutions will differ. The choice of $\theta_s = 0.035$ is motivated by Becker (2005) findings of abatement expenditures of firms reported in the US Census' PACE (Pollution Abatement Cost Expenditure) survey, that average abatement expenditures (across firms with and without any reported abatement spending) range from 1 to 3.3 percent of total expenditures.

[48]$(K/L)^H = 1/(K/L)^F = 1500/1600$. The foreign country has a roughly 10-percent greater relative endowment of capital. Based on national capital-labor ratios reported by Schott (2003), these relative capital-to-labor endowments roughly mirror the relationship between the U.S. (home) and their largest trading partner, Canada (foreign) in 1990.

[49]The percent-changes in each channel are calculated as log-differences.

[50]Calculated as (Scale+Composition) - Scale: 101-117.

a reduction in emissions intensity in the polluting sector due to the reallocation of resources to more productive firms (technique: -16 percent). Taken together, these results show trade liberalization for this country, holding a comparative advantage in dirty production, leading to an increase in emissions of 13 percent.

These results are repeated in the first two columns of Table 1, along with results from two additional comparisons. Column (3) presents results for the same combined framework, but in which the countries now have identical endowments.[51] In this scenario, the relative prices in the two countries are identical under autarky, and thus neither has a comparative advantage.[52] When trade costs begin to fall, the countries begin trading, but there is no change in the factor allocation in either sector, and the composition effect is zero. Reallocation of resources, within each sector, towards more productive firms, results in increased output (scale: +16 percent) and a reduction in emissions intensity in the polluting sector (technique: -16 percent). The results are equivalent to what would be obtained in a single-sector model with a neutral effect of productivity on firms' relative factor demands and abatement decision. As discussed above,[53] the allocation of labor and capital in each sector remains unchanged, and since productivity is neutral, and there is no change in relative factor costs, firms continue to make the same abatement-share decisions. Thus, the productivity effects of reallocation working through the scale and technique effects exactly offset each other and the trade liberalization leaves total emissions unchanged. These results emphasize, however, that even when the two countries have similar comparative advantage (due to relative endowments or environmental policies) it would be incorrect to conclude that trade has no affect on the environment. The substantial scale and technique effects, when heterogeneous firms respond to changes in trade costs, are driving important environmental and economic effects that would be missed by focusing solely on the aggregate effect of the trade liberalization.

The final comparison is presented in column (4) of Table 1, showing the results of a trade liberalization in a homogeneous-firm framework, and thus without cross-firm reallocation. In this scenario, the home country again has a relative abundance of labor[54] and a comparative advantage in clean production. The results are calibrated so that the two models–the combined framework and the homogeneous-firm framework–yield the same outcomes under autarky. As the country opens to trade, however, productivity in the homogeneous-firm scenario remains fixed. In addition, in the homogeneous-firm model of Copeland and Taylor

[51] $(K/L)^H = (K/L)^F = 1500/1600$.

[52] In addition, all home country outcomes are identical, under autarky, to those of the home country evaluated in the left–hand panel of Figure D.1 – thus, in comparison to that panel, the only difference is that the endowments of the foreign country now match those of the home country.

[53] See Footnote 41.

[54] $(K/L)^H = 1/(K/L)^F = 1500/1600$.

(2003), a rigid environmental policy, targeting firms' emissions intensity, θ_1, is equivalent to fixing the pollution tax, in terms of the polluting good (t/P_1),[55] e.g. at the autarky value. This rigidity, in turn, implies that a trade liberalization in the homogeneous-firm model will not generate a technique effect. By comparing the first and last set of results in Table 1, the addition of heterogeneous firms, leading to the endogenous growth of productivity and changes in the mass of firms within each sector, generates three key results.

First, in contrast to a homogeneous firm model with fixed endowments and technology, endogenous productivity gains in the combined framework mean that each country's production possibility frontier (PPF) is not fixed, and productivity gains magnify the scale effect. Second, as emphasized in *Proposition* 2, the rise in total output of both goods, driven by productivity gains, dampens the composition effect (the relative increase in market share of the comparative advantaged sector), compared to the homogeneous firm case. Though productivity gains are largest in the comparative advantage sector, the presence of productivity gains in both sectors means that some of the increased demand for the comparative advantage good is satisfied through productivity gains, rather than resource movement. Finally, the endogenous productivity gains in the combined framework contribute to reductions in the dirty sector's emissions intensity, even when rigid environmental policy targets firms' emissions intensity, which are the corollaries to *Proposition 2*.

Together, all of these forces lead to a trade-induced decline in emissions when the home country holds a comparative advantage in clean production. However, the sign of the trade-induced scale plus composition effect does not necessarily reflect the country's comparative advantage, in contrast to the homogeneous firm model developed by Copeland and Taylor (2003). In their homogeneous firm model, trade liberalization ultimately leads to movement along a country's fixed PPF and the composition effect will always exceed the scale effect. In the combined framework, since endogenous productivity gains magnify the scale effect and moderate the composition effect, the scale effect can dominate the country's composition effect. This outcome can be seen in Figure D.1, or by comparing columns (1) and (4) of Table 1.

The specific results shown in Table 1 are due, in part, to the similarities of the capital-labor endowments of the US and Canada, on which this exercise is based. If the home country's relative labor endowment were substantially larger, for example, $(K/L)^H = 1/(K/L)^F =$

[55] In their homogeneous-firm setup, $P_1 = p_1 = \frac{w^{1-\beta_1} i^{\beta_1}}{(1-\theta_1)(1-\alpha_1)}$, and $\alpha_1 P_1/t = (1-\theta_1)^{(1-\alpha_1)/\alpha_1}$. To simulate this, the homogeneous-firm comparison also holds $\alpha_1 P_1/t$ fixed at the two countries autarky values. Even without this additional aggregate rigidity, the endogenous productivity gains in the combined-framework generate an additional channel reducing emissions intensity, compared to a representative-firm model without export-selection, but with differentiated varieties (in which trade liberalization can lead to changes in the mass of operating firms and offered varieties).

1500/2000, the negative composition effect would dominate the scale effect, and the trade-induced scale plus composition effect would be negative in the combined framework results as well. Consequently, when environmental policy is fixed, these results emphasize that the scale plus composition effect does not necessarily indicate the country's overall environmental effect of trade. This is because trade liberalization also induces endogenous improvement, via cross-firm reallocation, that reduce the dirty sector emissions intensity, captured by the technique effect. These findings suggests that empirical work investigating the relationship between trade and the environment should attempt to disentangle the effects of trade working through these various channels to develop a more complete understanding of the ways in which trade affects environmental outcomes.

7.2 Moderating Effect of Productivity and Comparative Advantage

To further emphasize the ways that a country's comparative advantage and heterogeneous firm responses interact to influence the environmental effects of trade, this section considers the environmental outcome of a reduction in trade barriers in three scenarios: in the first case the two trading partners have equivalent endowments ($K^H/L^H = K^F/L^F = 1500/1500$) and environmental stringency ($\theta_1 = 0.035$). In the other two cases the relative capital abundance of the home country rises, thereby generating a rising comparative advantage in dirty production.[56] In each case, all other parameters, including environmental stringency, remain unchanged. In each case and each model the composition effect is calculated, from equation (23), as log-differences. Figure D.2 then presents the comparison of the combined framework and the homogeneous-firm model outcomes (denoted by "Δ"), by subtracting the composition effect obtained in the homogeneous-firm model, from that obtained in the combined framework when average productivity is endogenously determined.[57]

Figure D.2 shows that in the absence of a comparative advantage, the inclusion of heterogeneous firms has no affect on aggregate emissions: as previous analysis showed, the additional productivity gains working through the scale and technique effects offset one another in this case, and each model predicts the same (zero) change via the composition effect.[58]

[56] The second and third cases consider symmetric changes to each country's factor endowments: $K^H/L^H = 1/(K^F/L^F) = 1550/1450$ and $K^H/L^H = 1/(K^F/L^F) = 1600/1400$)

[57] The composition effect in each model is obtained by taking the log differences of the polluting sector market share, compared to the market share obtained under autarky.

[58] The fixed productivity level in the representative model is calibrated to mirror the autarky equilibrium in the heterogeneous firm model. In addition, composition effects are identical in the two models in the absence of variable trade costs (and with identical fixed production and trade costs in each sector and country), regardless of differences in their endowments and comparative advantage. See discussion of *Proposition 1.*

However, as the national comparative advantage more strongly diverges–the key channel influencing the overall sign of a trade liberalization for emissions outcomes–the trade-induced endogenous productivity growth moderating the composition effect also rises in magnitude. Compared to the results from a homogeneous-firm model, the composition effect is roughly one percentage point smaller when the comparative advantage is "moderate", and nearly two percentage points smaller as the endowments, and thus comparative advantage, of the two countries more strongly diverge. The results, which correlate with the conclusion emphasized by *Proposition 3,* highlight an additional challenge for empirical investigations of an environmental trade effect. On the one hand, a rise in the country's comparative advantage will tend to generate an environmental effect of trade. On the other hand, the rise in productivity in sector is also increasing with the country's comparative advantage, thus dampening the cross-sector effects of trade and making identification of an environmental effect of trade, working through the comparative advantage channel, more difficult.

7.3 An Application of the Combined Framework to Observed Empirical Findings

The final part of the simulation exercise is an application of the combined framework to empirical outcomes estimated by Levinson (2009). This exercise can address two relevant questions that are complicated in the original empirical estimation. First, what shocks (to trade costs, environmental stringency, or relative factor endowments) are consistent with observed trends in the country's scale, composition, and technique effects? And second, what is the relative importance of each shock, *ceteris paribus*, on each effect and on total emissions?

To begin, I again consider symmetric differences in relative factor endowments, with the home country having roughly 18 percent greater capital-to-labor ratio than the foreign,[59] and the foreign country also having less stringent environmental regulation target: $\theta_1^H = 0.035$ and $\theta_1^F = 0.01$, following evidence from Cole and Elliott (2005) that less capital-abundant countries have lower environmental regulation, on average. I then consider three shocks to the model: (1) a decline in variable trade costs, (2) an increase in environmental stringency in the home country, and (3) a relative factor expansion favoring clean production at home. The variable values and changes associated with each of the three scenarios are laid out in

[59] $K^H/L^H = 1/(K^F/L^F) = 1630/1500)$. The 18 percent relative capital-to-labor ratio target is a trade-weighted average of the capital-to-labor ratio of the U.S.'s top-five trading partners in 1990 (Canada, Japan, Mexico, Germany, U.K.). Trade (imports+exports) weights were calculated using trade balance data from the U.S. Census (https://www.census.gov/foreign-trade/balance/index.html) and capital-to-labor ratios are taken from Schott (2003).

Table 2. In each of the three scenarios the home country maintains a comparative advantage in dirty production (i.e. $P_1^H/P_2^H < P_1^F/P_2^F$). The raw values associated with each scenario, for imports, output, market share of the dirty sector, emissions intensity, and total emissions are laid out in Table 3.

The current exercise focuses on six outcomes documented by Levinson (2009): a +112 percent increase in imports, a +24 percent scale effect, a +3 percent trade-induced composition effect, a -12 percent overall composition effect, a -39 percent technique effect, and a -27 percent combined overall reduction in emissions.

Table 4 shows the affect of each shock on imports and on each of the three effects (scale, composition, and technique, as well as the total effect) as a percentage-change. The bottom row of Table 4 repeats the estimates of each channel found by Levinson (2009). The outcome of each scenario is emphasized in bold when it is within one percentage point of the corresponding result documented by Levinson (2009).

The first scenario considers a reduction in variable trade costs, calibrated to match the rise in imports and the small rise in the trade-induced composition effect. As seen in Tables 2 and 4, the combined framework precisely obtains these two outcomes with a reduction in trade costs from 45 to 3.5 percent ($\tau = 1.45$ to $\tau = 1.035$). Just as in Levinson (2009), the trade-induced composition effect is relatively small, and moves in the opposite direction of the overall composition effect. Unlike Levinson (2009), this exercise in the combined framework also reveals the role of increased trade on the overall scale (+11 percent) and technique effects (-11 percent).

The second scenario adds consideration of an increase in environmental stringency, calibrated to match the decline in the technique effect. As seen in Tables 2 and 4, the combined framework obtains this outcome, as well as matching the overall change in emissions, with an increase in the emissions intensity target for polluting firms from $\theta_1^H = 0.032$ to $\theta_1^H = 0.035$ (the baseline target). The increase corresponds to slightly less than a 10 percent increase in environmental stringency.

But, even with both shocks calibrated to observed outcomes, the combined framework still does not fully match the overall estimated scale and composition effects. To match the two remaining effects, the final scenario considers the effect of growth in relative factor shares that favors relatively clean output in the home country. Maintaining the symmetry in relative factor shares this means both a relative increase in labor at home, and a relative increase in capital in the foreign trading partner.[60] This type of relative factor expansion

[60] Specifically, the third scenario adds consideration of an increased endowments in both countries, but an increase (decrease) to the home (foreign) relative endowment of of labor from $K^H/L^H = 1/(K^F/L^F) = 1608/1243$ to $K^H/L^H = 1/(K^F/L^F) = 1630/1500$, the baseline case. This equates to roughly a 1 percent expansion of capital at home, and a 21 percent increase in productive labor inputs (the growth pattern is

generates both an increase in total output in the home country (a scale effect), but also a Rybczynski effect that generates a relative reduction in the return to labor (at home), thus also leading to a cross-sector composition effect that favors the clean sector. It is worth noting that Romalis (2004) documents a substantial relative capital expansion among many U.S. (home) trading partners (foreign) from 1960-1998, and finds that these expansions are important drivers of observed trade flows, what he terms a “quasi-Rybczynski effect.”[61] As seen in Tables 2 and 4, with the addition of this third shock,[62] the combined framework is able to precisely match each of the six outcomes estimated by Levinson (2009).

A few points of interest are raised by this exercise. First, no single shock to parameters is capable of generating the outcomes documented by Levinson (2009). This is most easily seen by noting that the trade-induced composition effect and the overall composition effect move in opposite directions–a feat that no single shock could accomplish. Secondly, it is interesting to note that, given the model parameters, in particular $\alpha_1 = 0.011$ (the technology parameter governing the efficiency of abatement estimated by Shapiro and Walker (2017)), the combined framework matches the estimated technique and overall changes in emissions with an increase in environmental stringency, measured by the target emissions intensity, of less than 10 percent. This contrasts with the nearly 100 percent increase in the emission tax implied by the results estimated by Shapiro and Walker (2017), building on a single-sector framework that does not account for the role of comparative advantage driving factor costs or firm entry and exit across sectors.[63]

The additional value added by calibrating the combined framework to reported outcomes from Levinson (2009), is to generate *ceteris-paribus* insights regarding the role of the corresponding shocks working through each of the scale, composition, and technique effects, as well as the overall change in emissions, which may be masked by empirical aggregation, or otherwise impossible to disentangle from other simultaneous shocks. Table 5 decomposes

reversed for the foreign trading partner).

[61] Romalis (2004) shows countries that experienced a relative expansion of capital from 1960–1998 also increased their export of capital-intense goods. His work also documents several of the countries that experienced the greatest relative increase in their capital inputs over the period (Japan, Singapore, Hong Kong, and Taiwan), which were among the U.S. top trading partners in 1990 (U.S Census data on trade balances: https://www.census.gov/foreign-trade/balance/index.html).

[62] As shown in Table 2, in the third scenario the increase in the emissions-intensity target (θ_s^H) is lowered very slightly, compared to the second scenario. Due to the relative expansion of factors favoring the cleaner sector, the environmental policy does not have to do as much work to match the documented change in total emissions.

[63] The environmental regulation parameter adjusted in the present set of simulated results is an emissions intensity target, θ_1^H. In this way, the implicit environmental “tax” is permitted to flexibly adjust to any changes in factor returns. From the model results, the transition from scenario 3 to the baseline case, implies a tax increase from 0.2362 to 0.2913, roughly a 21 percent increase in the environmental “tax”–still well below the increase implied by Shapiro and Walker (2017).

the changes to emissions in the calibrated outcome by effect (each row) and by shock (each column). Each of the scale, composition, and technique effects, shown in the first three rows, is obtained by taking logs of equation (23) and then taking the difference between the outcomes obtained and the baseline scenario. The total effect, in the last column, is the sum across each shock and equates to the combined values (matching Levinson (2009)) obtained in Table 4.

The *ceteris paribus* effect of the trade liberalization, in column (1), is equivalent to the outcome obtained in scenario 1 from Table 4. The reduction in trade barriers, generating the observed trade-induced change in imports and composition effect, raised output by +11.5 percent, lowered emissions intensity in the sector by -11.4 percent, shifted market share in favor of dirtier producers, captured by a +3 percent increase in the composition effect, and thus contributed a roughly 3.1 percent increase in emissions, *ceteris paribus*. Looking across each effect row, the trade liberalization is responsible for nearly half of the observed increase in output captured by the scale effect, and nearly one-third of the observed reductions in emissions intensity captured by the technique effect. This is roughly half the size of the trade-induced technique effect estimated by Cherniwchan (2017), by examining the role of within-plant responses to the trade liberalization represented by NAFTA. The differences could be due to the fact that in the combined framework trade liberalization does not generate within-firm cleanup, only reallocation across firms and sectors. Still, the insights afforded by the simulation exercise in the combined framework suggest that the simultaneous role of trade liberalization, working through all three effects, may in fact be quite important, even when the overall effect, driven largely by the composition effect due to the country's comparative advantage, appears to be relatively small.

The *ceteris paribus* effects of the increase in factor expansion in column (3) are obtained by comparing the results in scenario 3 with those obtained when each country's factor endowments are instead held equal to their baseline values. The remaining half of the scale effect and nearly the entire composition effect are driven by relative expansion of productive factors, favoring the cleaner sector. Finally, the *ceteris paribus* effects due to increases in environmental stringency, shown in column (2), are obtained by comparing the results in scenario 3 with those obtained when environmental stringency is instead set equal to its baseline value, $\theta_1^H = 0.035$. Unsurprisingly, an increase in environmental stringency puts substantial downward pressure on emissions, working through the technique effect. In the combined framework increased environmental stringency primarily works by inducing firms to increase their abatement investments, thereby driving a within-firm reduction in emissions intensity among all polluting firms. The increase in environmental stringency, the only within-firm adjustment channel at work in the combined framework, is responsible for two-thirds of the overall technique effect. The increase in stringency is also responsible for small reductions in the scale effect, and a relative increase in costs in the polluting sector thereby driving a small portion of the overall reduction via the composition effect.

8 Conclusion

Several important advances have been made in recent years improving understanding of how different factors and channels affect the relationship between trade and environmental outcomes. However, empirical research, motivated by homogeneous-firm models, has struggled to establish a strong link between trade liberalization, comparative advantage, and emissions changes. The combined framework, developed here, presents a potential explanation for this difficulty, and sets the stages for a more detailed and comprehensive understanding of the ways in which trade liberalization can work to affect aggregate outcomes, like emissions demand.

This is the first paper combining a heterogeneous-firm framework with cross-sector comparative advantage–driven by differences in countries relative endowments or environmental policy–to examine the aggregate environmental effects of trade. By focusing on the ways in which a country's comparative advantage influences the individual decisions of firms and affects aggregate emissions outcomes, the primary message of the resulting combined framework is at once both simple and complex. Simple in that it highlights the message that, when fixed costs are an important determinant of firms' export and production decisions, both comparative advantage, influencing cross-sector responses to trade liberalization, and heterogeneous firm responses within sectors are interacting to affect our environment. The paper's message, however, presents a more complex empirical challenge in that it suggests that research evaluating the effect of trade cost or environmental policy changes on environmental outcomes must carefully account for the ways in which factors driving within-sector firm-selection and production decisions interact with factors influencing cross-sector resources shifts.

The combined framework shows how the presence of heterogeneous-firms and fixed costs leads to endogenous productivity gains that can generate substantial traditional scale and technique effects, and moderate the composition effect, relative to a homogeneous-firm framework. Taken as a whole, the combined framework provides different messages for researchers and for policy makers. For policy makers, and the public, concerned that trade may motivate cross-country shifts in production and pollution driven by relatively lax environmental regulation, the combined framework emphasizes that simultaneous within sector reallocation of resources towards more productive firms will generate aggregate productivity gains that will tend to spillover to moderate the trade-induced rise in emissions, driven largely by the composition effect that is at the heart of this concern. However, for researchers, this same moderating effect means that identifying the various interactive effects of trade liberalization on environmental outcomes may be quite challenging as these simultaneous within and across sector channels work against each other, thus making it more likely that empirical investigation will find a small or null result when investigating the environmental effects of trade. Consequently, these results provide a theoretical rationale for the empirical results obtained by Antweiler et al. (2001) and Levinson (2009) who document surprisingly small composition effects corresponding with increased trade but large technique effects.

In addition, calibrating the combined framework to the outcomes and effects estimated by Levinson (2009) provides one example of the rich insights that can be gained from this new framework. Results from this exercise highlight how additional difficulties arise when shocks to trade costs may be simultaneous with changes in environmental regulation or relative factor expansion, and how each shock can work across all three of the scale, composition, and technique effects–an insight that may be lost with aggregate analysis.

The combined framework builds on work by Copeland and Taylor (2003) to show that identifying the ways in which trade liberalization is affecting the environment is aided by first separating the scale, composition and technique effects, and then analyzing the effects of the trade liberalization working through the heterogeneous responses of firms that drive each effect. The overall effect of the trade liberalization is still driven by the country's comparative-advantage, and in that sense, as in Copeland and Taylor (2003), the composition effect "is critically important to determining the effects of trade liberalization" (p. 113). However, the insight that endogenous productivity gains magnify the scale effect and moderate the composition effect leaves open the potential for scale effects of trade to dominate simultaneous composition effects. Thus, the results from the combined framework further suggest that empirical work focusing on the combined scale plus composition effect of trade may give the erroneous impression that a country holds a comparative advantage in dirty production, when in fact it does not. To get a more accurate estimate of the trade-induced composition effect, empirical work should attempt to separate the effect of trade on output (i.e. the trade-induced scale effect) from the other constituent channels.

Work disentangling the environmental effects of trade working through all the various channels is likely to continue to generate new important insights into our understanding of the effects of trade on the environment. Recent work by Cherniwchan (2017) incorporates some of these strategies to identify the environmental effects of NAFTA, showing that heterogeneous improvements in within-plant production techniques, could be responsible for up to two-thirds of the decline in the aggregate emissions intensity of manufacturing establishments following the implementation of the free trade agreement in the mid-1990s. Extending the combined framework to incorporate a within-firm response to trade liberalization changes could be a fruitful area for further work.

Interesting areas for further work include additional testing of the model's empirical implications and exploring the role of changing fixed costs and environmental regulations in firms entry and exit decisions as well as their abatement decisions. The model could also provide a framework in which to explore aspects of the Porter hypothesis and its variants (Porter and Linde (1995)) or, more generally, it could provide a useful framework for determining a more precise relationship between firm-productivity and total emissions demand. The framework can also be used to evaluate the potential relative magnitudes of environmental leakage induced by cross-country differences in relative environmental stringency, a particularly relevant concern for universal mixing pollutants like green house gasses (Elliott et al. (2010)).

Appendix A: Average Productivity, Aggregation, and Free Entry in the Closed Economy

This appendix briefly discusses the relationships between the productivity cut-off, average productivity, and aggregate outcomes that underlie the environmental results discussed in this paper, but are largely unchanged from those defined and derived by Bernard et al. (2007b).

The distribution of firms operating in a sector can be characterized by an ex-post distribution of productivity levels, which is bounded by the sector's cut-off productivity level, φ_s^*.

$$\mu_s(\varphi) = \begin{cases} \frac{g(\varphi)}{1-G(\varphi_s^*)} & \varphi \geq \varphi_s^* \\ 0 & \text{otherwise} \end{cases} \tag{A.1}$$

where $g(\varphi)$ is the density function of φ. The probability of drawing a productivity level above φ_s^* and remaining in the market is $[1 - G(\varphi_s^*)]$. Thus the probability distribution $\mu_s(\varphi)$ represents the conditional probability of successful entry.

Average productivity, $\tilde{\varphi}_s$, defined as

$$\tilde{\varphi}_s(\varphi_s^*) \equiv \left[\int_{\varphi_s^*}^{\infty} \varphi^{\sigma-1} \mu_s(\varphi) \mathrm{d}\varphi \right]^{\frac{1}{\sigma-1}} \tag{A.2}$$

is an output weighted productivity average across all firms operating in the market.[64] Using this characterization of average productivity, the aggregate price index and output level for a given sector from (2) and (3) can be rewritten simply as functions of the mass of firms and average price and output (respectively):

$$P_s = \left[\frac{1}{1 - G(\varphi_s^*)} \int_{\varphi_s^*}^{\infty} p(\varphi)^{1-\sigma} M_s g(\varphi) \mathrm{d}\varphi \right]^{\frac{1}{1-\sigma}} = M_s^{\frac{1}{1-\sigma}} p(\tilde{\varphi}_s) \tag{A.3}$$

$$Q_s = M_s^{\frac{1}{\rho}} \eta_s R P_s^{\sigma-1} \left(p(\tilde{\varphi}_s) \right)^{-\sigma} = M_s^{\frac{1}{\rho}} q_s(\tilde{\varphi}_s) \tag{A.4}$$

Firms will continue to enter the market until the expected value from entry, V_s, reaches zero. Firms entering the market must cover a separate fixed cost of entry, f_{es}, and then

[64] Using the fact that, from (3) , $q(\varphi_1)/q(\tilde{\varphi}_1) = (\varphi_1/\tilde{\varphi}_1)^{\sigma}$, $\tilde{\varphi}_s$ can be written as $\tilde{\varphi}_s^{-1} = \left[\int_{\varphi_s^*}^{\infty} \varphi^{-1} \left(q(\varphi_s)/q(\tilde{\varphi}_s) \right) g(\varphi) \mathrm{d}\varphi \right]$

face the continuous, exogenous, potential of an negative economic shock that forces them to shutdown, δ. The free entry condition is thus:

$$V_s = \frac{[1 - G(\varphi_s^*)]\bar{\pi}_s}{\delta} = f_{es}\frac{w^{1-\beta_s} i^{\beta_s}}{(1-\alpha_s)(1-\theta_s)} \tag{A.5}$$

where $[1 - G(\varphi_s^*)]$ represents the probability of successful entry. Combined with the zero-profit condition, and noting that $r(\varphi^{'})/r(\varphi^{''}) = \left(\varphi^{'}/\varphi^{''}\right)^{(\sigma-1)}$, the free entry condition can be re-written as a function of parameters and exogenous variables.

$$V_s = \frac{f_s}{\delta} \int_{\varphi_s^*}^{\infty} \left[\left(\frac{\varphi}{\varphi_s^*} \right)^{\sigma-1} - 1 \right] g(\varphi) \mathrm{d}\varphi = f_{es} \tag{A.6}$$

where $g(\varphi)$ is the ex-ante productivity distribution.

The value of entry is decreasing in the shutdown probability, δ, and increasing in the fixed costs of production. A higher rate of firm failure lowers the mass of incumbent firms and raises the probability drawing a productivity high enough to cover the costs of entry, lowering the productivity cut-off. Higher fixed costs of production imply that firms must draw a higher productivity to profitably serve the market.

In the steady state equilibrium, the mass of firms exiting due to adverse shocks is equal to the mass of entering firms,

$$\delta M_s = [1 - G(\varphi_s^*)] M_{es} \tag{A.7}$$

Firm entry and exit in any given sector does not affect the equilibrium zero-profit productivity cut-off or sector averages because δ is exogenous, and thus the productivity distribution of firms entering is equal to the distribution of firms exiting the market.

Appendix B: Autarky, Free Trade, and Costly Trade Equilibria

Existence of an Autarky Equilibrium –

The autarky or closed-economy equilibrium for a country is referenced by a vector of ten variables: $[\varphi_s^*,\ P_s,\ R,\ p_s(\varphi),\ w,\ i,\ t]$, $s \in \{1, 2\}$ in which φ_s^* is pinned down by the zero-profit condition and the free-entry condition in each sector. Factor prices w and i are determined by factor market clearing conditions and free-entry, and t_1 is exogenously determined. Aggregate prices and revenues are functions of average firm productivity, factor prices, and φ_s^*.

Choose labor as the numeraire good, so $w = 1$. From the free-entry condition (A.6), V_s is monotonically decreasing in φ_s^*. Thus (A.6) defines a unique equilibrium value of φ_s^*, as a function of model parameters and fixed variables.

From (A.2), φ_s^* uniquely determines $\tilde{\varphi}_s(\varphi_s^*)$. Combining the zero profit cut-off condition (11) with the fact that $r_s(\tilde{\varphi}_s) = (\tilde{\varphi}_s/\varphi_s^*)^{\sigma-1}\, r(\varphi_s^*)$, average revenues and profits (denoted by a "bar") can be expressed as functions of φ_s^* and factor rewards:

$$\begin{aligned}
\bar{r}_s &= \left(\frac{\tilde{\varphi}_s(\varphi_s^*)}{\varphi_s^*}\right)^{\sigma-1} \sigma f_s \frac{w^{1-\beta_s} i^{\beta_s}}{(1-\alpha_s)(1-\theta_s)} \\
\bar{r}_s &= \left(\frac{\tilde{\varphi}_s(\varphi_s^*)}{\varphi_s^*}\right)^{\sigma-1} \sigma f_s \zeta_s \left(w^{1-\beta_s} i^{\beta_s}\right)^{1-\alpha_s} t^{\alpha_s}
\end{aligned} \tag{B.1}$$

where $(1-\theta_s)$ is given in (8), and $\zeta_s = \alpha_s^{-\alpha_s}(1-\alpha_s)^{(\alpha_s-1)}$ is comprised of technology parameters from the assumed Cobb-Douglas production structure. Average profits are then given by

$$\bar{\pi}_s = \left[\left(\frac{\tilde{\varphi}_s(\varphi_s^*)}{\varphi_s^*}\right)^{\sigma-1} - 1\right] f_s \zeta_s \left(w^{1-\beta_s} i^{\beta_s}\right)^{1-\alpha_s} t^{\alpha_s}$$

In each sector, total payments for factors of production (denoted with the p superscript) equals total revenue minus profits:

$$wL_s^p + iK_s^p + tZ_s^p = R_s - \Pi_s$$

and combining free entry (A.6) with steady-state stability, $[1 - G(\varphi_s^*)] \cdot M_{es} = \delta \cdot M_s$, the total value of payments used for entry in a sector is equal to total sector profits:

$$\Pi_s = M_s \bar{\pi}_s = M_{es} f_{es} \zeta_s \left(w^{1-\beta_s} i^{\beta_s}\right)^{1-\alpha_s} t^{\alpha_s} = w_s L_s^e + i_s K_s^e + tZ_s^e \tag{B.2}$$

Thus, using the market clearing conditions in (13), the sum of total payments to factors in each sector equals total revenue, recalling that sector 1 is assumed to be the polluting sector and $Z_2 = 0$

$$\begin{aligned} wL_1 + iK_1 + tZ_1 &= R_1 \\ wL_2 + iK_2 &= R_2 \end{aligned} \tag{B.3}$$

Since this is true for both sectors, aggregate revenue equals aggregate income (where the "bar" on a factor denotes it's fixed endowment level):

$$w\bar{L} + i\bar{K} + tZ_1 = R$$

Equilibrium factor demands in each sector follow from the Cobb-Douglas production function, since factor intensities for production and entry are identical, and thus total payments to factors are a constant share of sector revenues:

$$L_s = \frac{(1-\alpha_s)(1-\beta_s)R_s}{w}, \qquad K_s = \frac{(1-\alpha_s)\beta_s R_s}{i}, \qquad Z_1 = \frac{\alpha_1 R_1}{t} \tag{B.4}$$

Cost minimization further implies that relative factor intensities are a function of each sector's production technology and relative factor returns:

$$\frac{L_s}{K_s} = \frac{i}{w}\frac{(1-\beta_s)}{\beta_s} = i\frac{(1-\beta_s)}{\beta_s} \tag{B.5}$$

As suggested by Bernard et al. (2004), the factor market clearing conditions applied to capital and labor can be expressed as ratios:

$$\frac{\bar{K}}{\bar{L}} = \lambda_{L_1}\left(\frac{K_1}{L_1}\right) + (1-\lambda_{L_1})\left(\frac{K_2}{L_2}\right), \qquad \lambda_{L_s} = \frac{L_s}{\bar{L}}$$

$$\frac{\bar{L}}{\bar{K}} = \lambda_{K_1}\left(\frac{L_1}{K_1}\right) + (1-\lambda_{K_1})\left(\frac{L_2}{K_2}\right), \qquad \lambda_{K_s} = \frac{K_s}{\bar{K}}$$

where bars denote the country's endowment. Substituting in (B.5), these equations can now be rearranged to find each country's equilibrium allocations of labor and capital as functions of endogenous factor returns, model parameters and country endowments:[65]

[65]Using these factor allocations is the clearest way to see that the Rybczynski theorem holds in this framework. Holding factor prices fixed, a rise in the country's capital endowment will raise capital and labor, and consequently output, in sector 1 (the dirty sector) and lower it in sector 2 (the clean sector).

$$L_1 = \frac{i\bar{K} - \left(\frac{\beta_2}{1-\beta_2}\right)\bar{L}}{\left(\frac{\beta_1}{1-\beta_1}\right) - \left(\frac{\beta_2}{1-\beta_2}\right)}, \qquad L_2^n = \frac{\left(\frac{\beta_1}{1-\beta_1}\right)\bar{L} - i\bar{K}}{\left(\frac{\beta_1}{1-\beta_1}\right) - \left(\frac{\beta_2}{1-\beta_2}\right)} \tag{B.6}$$

$$K_1 = \frac{\left(\frac{\beta_1}{1-\beta_1}\right)\bar{K} - \left(\frac{\beta_1}{1-\beta_1}\right)\left(\frac{\beta_2}{1-\beta_2}\right)\frac{1}{i}\bar{L}}{\left(\frac{\beta_1}{1-\beta_1}\right) - \left(\frac{\beta_2}{1-\beta_2}\right)}, \qquad K_2 = \frac{\left(\frac{\beta_1}{1-\beta_1}\right)\left(\frac{\beta_2}{1-\beta_2}\right)\frac{1}{i}\bar{L} - \left(\frac{\beta_2}{1-\beta_2}\right)\bar{K}}{\left(\frac{\beta_1}{1-\beta_1}\right) - \left(\frac{\beta_2}{1-\beta_2}\right)} \tag{B.7}$$

Aggregate income in each country equals aggregate expenditure and, recalling that labor is the numeraire good and that consumers spend a constant share of income in each sector, total factor payments can be written as:

$$R = \bar{L} + i\bar{K} + tZ_1 = \frac{\bar{L} + i\bar{K}}{1 - \alpha_1\eta} \tag{B.8}$$

where Z_1 is taken from (B.4)

In both countries, total sector payments to capital are a constant share, $(1-\alpha_s)\beta_s$, of sector revenues which are a constant share, η_s,[66] of total expenditures, R, which also equal total factor payments:

$$iK_s = (1-\alpha_s)\beta_s\eta_s\left[\frac{\bar{L} + i\bar{K}}{1 - \alpha_1\eta}\right] \tag{B.9}$$

where both the factor returns and sector factor allocations are endogenous. Then substituting for equilibrium capital allocations, K_s, from (B.7) and rearranging yields the equilibrium capital return.

$$i = \frac{\bar{L}}{\bar{K}} \cdot \frac{\beta_2 + \eta(\beta_1 - \beta_2 - \alpha_1\beta_1)}{1 - \beta_2 - \eta[\beta_1 - \beta_2 + \alpha_1(1-\beta_1)]} \tag{B.10}$$

In the autarky equilibrium, given the choice of numeraire, the relative return to capital can be expressed as a function of the country's endowments and technology. As can be seen in (B.5), and as in Copeland and Taylor (2003), cost-minimization by firms means that the relative capital and labor demands by firms, and by each sector, are not a function of the country's prevailing environmental policy. Environmental policy influences firm's net-output choice, but not their relative demands for capital and labor, and consequently does not directly influence the equilibrium relative return to capital.

With factor returns and environmental policy determined, output prices, $p_s(\tilde{\varphi}_s)$, follow

[66] Recalling that $\eta_2 = 1 - \eta_1 = 1 - \eta$ and $\alpha_2 = 0$.

from the sector pricing rule (9). In a closed economy, price indices in each sector are given by (12) and $M_s = R_s/\bar{r}_s$. Using (B.4), total sector revenue can be written as: $R_s = (L_s + iK_s)/(1 - \alpha_s)$, and average sector revenue, given by (B.1), is determined by φ_s^*, factor returns, and environmental stringency, which were solved for above. Thus, the mass of firms is solved as a function of factor prices, endowments, and the productivity cut-off and independent of the aggregate emissions level.

Emissions demand from (B.4) can then be solved as a function of equilibrium values:

$$Z_1 = \frac{\alpha_1 R_1}{t} = Z_1(w,\, i,\, t,\, \bar{K},\, \bar{L},\, \varphi_1^*) \tag{B.11}$$

Given the recursive nature of the system, as in Copeland and Taylor (2003), changes to emissions demand are determined via shocks to factor endowments, the emissions tax, or available abatement technology, or endogenous changes to factor prices. In the combined framework, emissions are also influenced by endogenous changes in productivity.

Individual firms take the emissions policy (via t_1) as given, and output, capital and labor allocations, and other endogenous variables can thus be solved for in equilibrium independent of the emissions level. Per-unit emissions are determined as a relationship between these equilibrium values and the emissions tax. Total emissions can then be determined by scaling average per-unit emission by the equilibrium level of output in the polluting sector. This fully characterizes the closed-economy equilibrium identified by the vector $\{\varphi_1^*,\, \varphi_2^*,\, P_1,\, P_2,\, R,\, p_1(\varphi),\, p_2(\varphi),\, w,\, i,\, t\}$.

This concludes the discussion.

Existence of a Free Trade Equilibrium

This discussion reintroduces country notation. The free trade equilibrium is referenced by a vector of ten variables for each country, $n \in \{H, F\}$: $\{\varphi_s^{*n},\, P_s^n,\, R^n,\, p_s^n(\varphi),\, w^n,\, i^n,\, t^n\}$, $s \in \{1, 2\}$. In the free trade equilibrium, all producers in each country and sector will offer varieties in both countries, and consumer price indices will equalize and are given by:

$$P_s^H = P_s^F = P_s = \left[M_s^H \left(p_s^H(\tilde{\varphi}_s^H) \right)^{1-\sigma} + M_s^F \left(p_s^F \tilde{\varphi}_s^F) \right)^{1-\sigma} \right]^{\frac{1}{1-\sigma}} \tag{B.12}$$

The common price indices are lower as firm prices fall and as more firms produce, in either country. The absence of any trade costs implies that all operating firms in both countries will also export. With similar preferences and technology, profit maximization implies the same equilibrium price in both the domestic (d) and export (x) markets:

$$p_s^n(\varphi) = p_{sd}^n(\varphi) = p_{sx}^n(\varphi) = \frac{(w^n)^{1-\beta_s}(i^n)^{\beta_s}}{(1-\theta_s^n)(1-\alpha_s)\rho\varphi} \tag{B.13}$$

The free trade equilibrium is determined by the following ten equilibrium conditions for each country: firm's pricing rule in each sector (9), free-entry in each sector (A.6), capital and labor factor market clearing (13), equilibrium price indices implied be consumer and producer optimization in each sector (B.12), the requirement that world expenditure on a country's varieties equals the value of their production ($R^n = R_1^n + R_2^n = w^n(L_1^n + L_2^n) + i^n(K_1^n + K_2^n) + t^n Z_1^n$), and the exogenously determined environmental policy (t^n). Choosing labor in the home country as the numeraire ($w^n = 1$) the remaining equilibrium variables are solved from the remaining system of seventeen equations (for home and foreign together), with rigid environmental policy in both countries.

When countries implement identical environmental taxes or emissions intensity targets ($t^H = t^F$ or $\theta_1^H = \theta_1^F$) the free trade equilibrium can be explicitly characterized by factor price equalization (FPE). Factor price equalization (FPE) is a theoretical simplification that can be exploited to demonstrate that free trade in goods can replicate free-movement of factors. In other words, when countries have the option to trade their output or inputs, and either option chosen will result in the same equilibrium factor returns. In contrast to the to the autarky case, under free trade, if a country has a relatively larger endowment of capital than labor they can trade goods that are capital intense and thus increase the relative demand for capital above what it would be under autarky. With identical production technologies and environmental policy across countries, the ability to freely trade output will lead factor prices to equalize across countries. The FPE result also relies on the absence of factor intensity reversals, i.e. sectors are assumed to use similar input ratios across countries. The FPE set requires the standard assumption that each of the country's factor endowment ratios lie between their equilibrium integrated factor intensities, or what is sometimes called their "cone of diversification." If this does not hold, only one good would be produced and factor returns would mirror a single good case in which they become functions of their marginal products and respective country endowments.

Specifically, FPE and the choice of the home country labor as the numeraire good implies: $w^F = w^H = w = 1$ and $i^F = i^H = i$. Cost minimization and identical consumer preferences and marginal factor productivity across countries means that relative factor demands under free trade are identical to those given in (B.4) and (B.5), with the addition of country-specific notation on factor returns and allocations, and expenditures.

FPE and similar consumer preferences and technology in each country implies that equation (B.9) can be written as: $i(K_s^H + K_s^F) = (1 - \alpha_s)\beta_s\eta_s \left[\frac{w(\bar{L}^H + \bar{L}^F) + i(\bar{K}^H + \bar{K}^F)}{1 - \alpha_1\eta}\right]$, and substituting for the equilibrium capital allocations (from (B.7)) and rearranging yields the free trade FPE corollary to (B.10).[67]

Given FPE, factor prices, $w^F = w^H = w = 1$ and $i^F = i^H = i$, have been solved for, and environmental policy is exogenously determined, and identical across countries ($\theta_1^H = \theta_1^H = \theta_1$).

Firm's prices, $p_s^n(\varphi)$, are solved for given the pricing rule in (B.13), factor prices, and the country's environmental policy target, $(1 - \theta_s^n)$ given by (8). Each country's revenue, R^n, follows from (B.8) and equilibrium factor returns. Productivity cut-offs, φ_s^{*n}, are determined by the free-entry condition in (A.6).

Under free trade, price indices in each sector will equalize and are given by (B.12). Average productivity, $\tilde{\varphi}_s^n$, is determined solely by φ_s^{*n} in equation (A.2), and $M_s^n = R_s^n / \bar{r}_s^n$. A firm's revenue and profits under free trade are given by

$$\begin{aligned} r_s^H(\varphi) &= r_{sd}^H(\varphi) + r_{sx}^H(\varphi) = \left[1 + \frac{R^F}{R^H}\right] r_{sd}^H(\varphi) \\ \pi_s^H(\varphi) &= \frac{r_s^H(\varphi)}{\sigma} - f_s \frac{w^{1-\beta_s} i^{\beta_s}}{(1-\alpha_s)(1-\theta_s)} \end{aligned} \tag{B.14}$$

and average revenue is given by equation (B.1). From the free entry condition in equation (A.6), which applies when there is no selection between exporting and non-exporting firms, average revenue is determined by the productivity cut-off and factor prices. From equation (B.3), sector revenues are given by factor allocations (recognizing that sector 1 revenue can be written as $R_1^n = (iK_1^n + L_1^n)/(1 - \alpha_1)$) and factor returns for which we have solved.

As under autarky, emissions demand, $Z_1^n = \alpha_1 R_1^n / t^n$, can then be solved as a function of equilibrium values. Thus, given FPE (and identical exogenous environmental target in both countries), this completes the characterization of the equilibrium vector: $\{\varphi_s^{*n}, P_s^n, R^n, p_s^n(\varphi), w^n, i^n, t^n\}$, for $n \in \{H, F\}$ and $s \in \{1, 2\}$.

This concludes the discussion.

Free Entry under Costly Trade –

The introduction of fixed and variable trade costs results in market segmentation, according to productivity. Firms that draw a productivity above the entry cut-off enter and serve the domestic market as under autarky. Of those, a share will draw a productivity level high

[67] This also demonstrates how, under free trade, the FPE equilibrium (with similar environmental policy) can replicate an integrated equilibrium, when $\bar{L} = \bar{L}^H + \bar{L}^F$ and $\bar{K} = \bar{K}^H + \bar{K}^F$.

enough to allow them to cover the additional fixed exporting costs and enter the export market. This share is given by:

$$\chi_s^H = \frac{\left[1 - G(\varphi_{sx}^{*H})\right]}{\left[1 - G(\varphi_s^{*H})\right]} \tag{B.15}$$

As in the autarky or free trade cases, firms will choose to enter the market if they expect to earn revenues sufficient to cover the costs of entry. With the potential to earn profits in the foreign export market as well as the domestic, firm revenue and profits under costly trade differ based on a firm's export status:

$$\begin{aligned}
r_s^H(\varphi) &= \begin{cases} r_{sd}^H(\varphi) & , \quad \text{non} - \text{exporter} \\ r_{sd}^H(\varphi) + r_{sx}^H(\varphi) = \left[1 + \tau_s^{1-\sigma}\left(\frac{P_s^F}{P_s^H}\right)^{\sigma-1}\left(\frac{R^F}{R^H}\right)\right] r_{sd}(\varphi) & , \quad \text{exporter} \end{cases} \\
\pi_{sd}^H(\varphi) &= \frac{r_{sd}^H(\varphi)}{\sigma} - f_s \frac{(w^H)^{1-\beta_s}(i^H)^{\beta_s}}{(1-\alpha_s)(1-\theta_s^H)} \\
\pi_{sx}^H(\varphi) &= \frac{r_{sx}^H(\varphi)}{\sigma} - f_{sx} \frac{(w^H)^{1-\beta_s}(i^H)^{\beta_s}}{(1-\alpha_s)(1-\theta_s^H)}
\end{aligned} \tag{B.16}$$

Under costly-trade, these profit and revenue equations give rise to two zero-profit entry cut-offs in each country: one for entry to the domestic market, φ_s^*, given by (11) and an additional higher cut-off, φ_{sx}^*, governing entry into the export market, given by (21). The two entry cut-offs are related just as in Bernard et al. (2007b) by (22).

The costly trade corollary to the free-entry condition in equation (A.6) is written as

$$V_s^H = \frac{[1 - G(\varphi_s^*)]}{\delta}\left[\bar{\pi}_{sd}^H + \chi_s^H \bar{\pi}_{sx}^H\right] = f_{es}\frac{(w^H)^{1-\beta_s}(i^H)^{\beta_s}}{(1-\theta_s^H)(1-\alpha_s)} \tag{B.17}$$

where the average profit earned in each market is equal to the profits earned by a firm with average productivity in each segment: $\bar{\pi}_{sd}^H = \pi_{sd}(\tilde{\varphi}_{sd})$ and $\bar{\pi}_{sx}^H = \pi_{sx}(\tilde{\varphi}_{sx})$.

Similarly to the autarky or free trade cases, the free-entry condition can be written as a function of parameters and productivity cut-offs as

$$V_s^H = \frac{f_s}{\delta}\int_{\varphi_s^{*H}}^{\infty}\left[\left(\frac{\varphi}{\varphi_s^{*H}}\right)^{\sigma-1} - 1\right] g(\varphi)\mathrm{d}\varphi + \frac{f_{sx}}{\delta}\int_{\varphi_{sx}^{*H}}^{\infty}\left[\left(\frac{\varphi}{\varphi_{sx}^{*H}}\right)^{\sigma-1} - 1\right] g(\varphi)\mathrm{d}\varphi = f_{es} \tag{B.18}$$

The expected value of entry is determined by the expected value of entering and serving the domestic market, plus a positive term capturing the expected value of entering and serving the foreign market. Thus, as in autarky, the value of entry is monotonically decreasing in φ_s^*.

Goods and Factor Markets

As in autarky, the mass of failing incumbent firms that exit is replaced by new entering firms drawing a productivity high enough to allow them to cover their production costs.

Under costly trade the sector price index is now influenced by the share of foreign producers that are productive enough to export as well as domestic producers, and is given by

$$P_s^H = \left[M_s^H \left(p_{sd}^H(\tilde{\varphi}_s^H) \right)^{1-\sigma} + \chi_s^F M_s^F \left(\tau_s p_{sd}^F(\tilde{\varphi}_{sx}^F) \right)^{1-\sigma} \right]^{\frac{1}{1-\sigma}} \tag{B.19}$$

Price indices vary across countries due to differences in the mass of operating and exporting firms, in factor prices, and the presence of trade costs. Finally, equilibrium sector revenues must now account for expenditures by both domestic and foreign consumers:

$$R_s^H = M_s^H \eta_s R^H \left(\frac{p_{sd}^H(\tilde{\varphi}_{sd}^H)}{P_s^H} \right)^{1-\sigma} + \chi_s^H M_s^H \eta_s R^F \left(\frac{\tau_s p_{sd}^H(\tilde{\varphi}_{sx}^H)}{P_s^F} \right)^{1-\sigma} \tag{B.20}$$

where the first term captures revenues earned in sector s from domestic sales, and the second are revenues earned by the share of operating firms productive enough to also export. This equilibrium condition implies that all goods markets, world wide, will clear.

Existence of a Costly Trade Equilibrium –

The costly trade equilibrium is referenced by a set of 14 variables, each, for home and foreign: $\{\varphi_s^{*n},\ \varphi_{sx}^{*n},\ P_s^n,\ p_s^n(\varphi),\ p_{sx}^n(\varphi),\ w^n,\ i^n, t^n,\ R^n\}$ for $s \in \{1,2\}$ and $n \in \{H,F\}$. These variables are determined by the following equilibrium conditions for each country: the free entry condition for each sector (B.18), the export productivity cut-off relationship for each sector (22), the pricing rules for each sector (9) and (19), costly trade price indices for each sector (B.19), capital and labor factor market clearing conditions (13), and the goods market clearing condition for each sector (B.20) ensuring that global on a country's varieties equals the value of their production. Environmental policy is assumed to be set exogenously each country.

Continue to hold home-country labor as the numeraire good, and thus $w^H = 1$.

Suppose that the factor price vector $\{1,\ i^H,\ t^H,\ w^F,\ i^F,\ t^F\}$ is known. Labor and capital endowments continue to be fixed in each country and the share allocated to each sector must account for entry as well as export and domestic production: $L_s^n = L_s^{ne} + L_s^{np} + L_s^{nx}$ and $K_s^n = K_s^{ne} + K_s^{np} + K_s^{nx}$ for $s \in \{1,2\}$ and $n \in \{H,F\}$. By adding country-specific notation to the factor prices in (B.6) and (B.7), to accommodate the fact that factor prices now differ across countries, the eight cross-sector allocation of factor endowments of capital and labor, $\{K_s^n,\, L_s^n\}$, can be obtained. In the costly trade equilibrium, total sector revenue can be shown to be: $R_1^n = (w^n L_1^n + i^n K_1^n)/(1-\alpha_1)$ and $R_2^n = w^n L_2^n + i^n K_2^n$. Thus, factor prices and factor allocations pin down sector revenue in each sector in each country, $\{R_s^n\}$, and total revenue, $R^n = R_1^n + R_2^n$, is solved for independently of the level of emissions.

The pricing rule (19) determines the eight average variety prices, $\{p_{sd}^n(\tilde{\varphi}_s^n),\, p_{sx}^n(\tilde{\varphi}_{sx}^n)\}$, as a function of factor returns, the emissions tax, the trade costs parameter, and productivity.

With wages, prices, and total revenues identified, the eight productivity cut-offs, $\{\varphi_s^{n*},\, \varphi_{sx}^{n*}\}$ and four sector price indices are the solution to a system of six equations for each sector given by (19), (22), and (B.18). In solving these equations, substitute the mass of firms given by $M_s^n = R_s^n/\bar{r}_s^n$, the probability of exporting given by $\chi_s^n = (1 - G(\varphi_{sx}^{*n}))/(1 - G(\varphi_s^{*n}))$, average revenue is given by

$\bar{r}_s^n = \left[(\tilde{\varphi}_s^n(\varphi_s^{*n})/\varphi_s^{*n})^{\sigma-1} f_s + \chi_s^n\, (\tilde{\varphi}_{sx}^n(\varphi_{sx}^{*n})/\varphi_{sx}^{*n})^{\sigma-1} f_{sx}\right] \sigma((w^n)^{1-\beta_s}(i^n)^{\beta_s})/((1-\theta_s^n)(1-\alpha_1))$, and $(1-\theta_s)$ given by (8). Thus, making use of the fact that these are functions of the six unknowns in each sector $\{\varphi_s^{*n},\, \varphi_{sx}^{*n},\, P_s^n\}$, they are solved for given the equilibrium wage vector, and equilibrium sector revenue which were solved for above. Thus, given factor returns, all other elements of the equilibrium vector are identified for each country.

The equilibrium capital and labor returns themselves are pinned down by the requirement that total industry revenues equal factor payments for each country and industry: $R_1^n = (w^n L_1^n + i^n K_1^n)/(1-\alpha_1)$ and $R_2^n = w^n L_2^n + i^n K_2^n$. The emissions tax is assumed to be determined exogenously, by a separate political economy process, and thus all key model variables are solved except for the emissions level.

The key feature of the present framework regards the equilibrium level of emissions and the recursive nature of the model as in Copeland and Taylor (2003). Total sector revenue, the mass of firms, and national income can be solved independently of the emissions level to determine relative wages and factor allocations. These equilibrium values can then be plugged into (B.11) to determine the equilibrium level of emissions demand.

This concludes the discussion.

Appendix C: Proofs and Supporting Material

Proof of proposition 1 –

In the move from autarky to free trade there is no differential selection into exporting, across firms. The zero profit productivity cut-off, φ_s^{*n}, where $n \in \{H,\, F\}$ denotes the country, is determined by (A.6) as a function of fixed variables and parameters and remains unchanged. Thus, in the transition from autarky to free trade, the productivity cut-off is unchanged. Average productivity, $\tilde{\varphi}^n$, is determined by (A.2) and when the productivity cut-off does not change, average productivity remains unchanged as well.

Secondly, aggregate emissions demand, under autarky and trade, can be expressed as in (17). Recognizing that $\bar{r}_s^n = \bar{p}_s^n \cdot \bar{q}_s^n$, average output under autarky and free trade can be written as $q(\tilde{\varphi}_s^n) = \left(\tilde{\varphi}_s^n/\varphi_s^{*n}\right)^{\sigma} q_s^{*n} = \left(\tilde{\varphi}_s^n/\varphi_s^{*n}\right)^{\sigma} (\sigma-1) f_s \varphi_s^{*n}$.[68] When there is no change in the productivity cut-off or relative stringency of environmental policy, then average productivity, average output, and firms' abatement investment, θ_1^n, remain unchanged. Any changes to emissions demand are working through changes in relative factor returns driving the mass of firms and varieties in each sector, given by $M_s^n = R_s^n/\bar{r}_s^n$. More generally, under autarky or trade, emissions demand is given by (16), which can be re-written making use of equilibrium conditions in (B.3):

$$Z_1^n = \frac{\alpha_1 R_1^n}{t_1^n} = \frac{\alpha_1}{t_1^n} \frac{\eta(i^n K_1^n + w^n L_1^n)}{1-\alpha_1} \tag{C.1}$$

Using the price index given in (12), relative prices under autarky are given by

$$\frac{P_1^n}{P_2^n} = \left(\frac{M_1^n}{M_2^n}\right)^{\frac{1}{1-\sigma}} \frac{p_1^n(\tilde{\varphi}_1^n)}{p_2^n(\tilde{\varphi}_2^n)} \tag{C.2}$$

Using (18), $R_1^n = \eta R^n$ and $R_2^n = (1-\eta) R^n$, average revenue from (B.1), and the pricing rule (9), the relative price index can be simplified to

$$\frac{P_1^n}{P_2^n} = \left(\frac{\eta}{1-\eta} \frac{f_2}{f_1}\right)^{\frac{1}{1-\sigma}} \frac{\varphi_2^{*n}}{\varphi_1^{*n}} \left[\frac{1}{(1-\theta_1^n)(1-\alpha_1)} \left(\frac{i^n}{w^n}\right)^{\beta_1-\beta_2}\right]^{1/\rho} \tag{C.3}$$

[68] When a country opens to trade, firm's export prices may differ from their domestic prices due to variable trade costs, and the pricing rule is given by (19). Using the relative relationship between firms with two different levels of output, average export output is given similarly to domestic, by $\bar{q}_{sx} = \left(\tilde{\varphi}_{sx}/\varphi_{sx}^*\right)^{\sigma} q_{sx}^*$. The output of a firms with the minimum productivity required to cover the fixed export costs is given by $q_{sx}^* = r_{sx}^*/p_{sx}^* = (\sigma-1) f_{sx} \varphi_{sx}^*/\tau$. Thus, average firm size or revenue, under trade, is given by $\bar{r}_s = \bar{r}_{sd} + \chi_s \bar{r}_{sx} = \bar{q}_{sd}\bar{p}_{sd} + \chi_s \bar{q}_{sx}\bar{p}_{sx}$. There are no trade costs under free trade, i.e. $\tau = 1$ and $f_{sx} = 0$, and all firms who successfully enter will also export: $\chi_s = 1$. Domestic and export prices are equivalent and given by (B.13). Average output and thus average firm revenue can be further reduced to a function of parameters and productivity cut-offs: $\bar{r}_s = [\left(\tilde{\varphi}_s/\varphi_s^*\right)^{\sigma} (\sigma-1) f_s \varphi_s^*]\bar{p}_s$.

where $\beta_1 > \beta_2$ and $(1-\theta_s^n)$ is given by (8).[69]

The relative abundance of capital in the home country, compared to the foreign, implies a lower relative capital return in the home country under autarky, as can be seen in (B.10). Assuming $\beta_1(1-\alpha_1) > \beta_2$, the lower relative capital return implies a lower relative output price for goods in sector 1, $P_1^H/P_2^H < P_1^F/P_2^F$, as long as the relative price relationship is not reversed by a significantly more stringent environmental policy (that would substantially raise θ_1^n).[70] Under a regime of free trade, relative prices in each country will equalize: $P_1^H/P_2^H = P_1^F/P_2^F$. Thus, when countries pursue a rigid environmental policy (e.g. targeting firm's emissions intensity, θ_1^n), in the move from autarky to free trade, the relative return to capital in the home country rises, and falls in the foreign country. The change in factor returns, and corresponding shift of resources into sector 1 at home (seen in (B.6) and (B.7)), raises the mass of firms and, from (C.1) with labor as the numeraire good, raises emissions demand in sector 1 in the home country.[71]

This concludes the proof.

Proof of proposition 2 –

(a) Other things equal an increase in average productivity puts downward pressure on prices and price indices in both sectors in both countries and thus the gains in productivity lead to increases in real output, $Q_s = R_s/P_s$, thereby raising emissions demand via the scale effect.

(b) Under autarky, relative price indices are given by (C.3). Thus, assuming $\beta_1 > \beta_2$, the larger relative endowment of capital in the home country, implies that the relative price index, P_1^n/P_2^n, is lower in the home country than in the foreign under autarky as long as higher environmental stringency does not reverse the relative costs of the sectors.

Under costly trade relative prices are given by

$$\frac{P_1^n}{P_2^n} = \left[\frac{M_1^n\left(p_{1d}^n(\tilde{\varphi}_1^n)\right)^{1-\sigma} + \chi_1^j M_1^j\left(\tau_1 p_{1d}^j \tilde{\varphi}_1^j)\right)^{1-\sigma}}{M_2^n\left(p_{2d}^n(\tilde{\varphi}_2^n)\right)^{1-\sigma} + \chi_2^j M_2^j\left(\tau_2 p_{2d}^j \tilde{\varphi}_2^j)\right)^{1-\sigma}}\right]^{\frac{1}{1-\sigma}} \qquad \text{for } j \neq n \qquad \text{(C.4)}$$

[69] When all firms are identical ($\varphi = 1$), and the elasticity of substitution between varieties is infinite, and consumers split their consumption between sectors equally ($\eta = 0.5$), equation (C.3) is identical to the free-entry condition developed by Copeland and Taylor (2003) (p.31), which in turn determines factor returns.

[70] Relatively higher environmental stringency contributes to higher costs and thus the average price in sector 1, moderating and possibly reversing the comparative advantage based on relative endowment differences.

[71] As discussed in the text, rigid environmental policy could come in the form of a fixed emissions tensity target (θ_1) or a fixed tax (t_1). A rigid emissions intensity target, θ_1, implies that changes in the relative return to capital may induce changes in the implicit tax, t_1. From equation (8), with labor as the numeraire, any changes to i (e.g. Δ), will always be larger than corresponding changes in t_1 (i.e. Δ^{β_1}) required to maintain a fixed θ_1: $\left(\frac{i^{\beta_1}}{t}\frac{\alpha_1}{1-\alpha_1}\right)^{\alpha_1} = \left(\frac{(\Delta i)^{\beta_1}}{(\Delta^{\beta_1})t}\frac{\alpha_1}{1-\alpha_1}\right)^{\alpha_1}$.

and relative prices converge to their autarky values as $\tau_s \to \infty$ and as $f_{sx} \to \infty$. Under free trade, $P_1^H = P_1^F$ and $P_2^H = P_2^F$. As $\tau_s \to 1$ and as $f_{sx} \to 0$, prices converge to their free trade values and thus P_1^n/P_2^n rises in the home country and falls in the foreign.

Barring cross-sector differences in fixed or trade costs, from (22) the differences in prices implies that the export cut-off is closer to the entry cut-off in the comparative advantage sector. Since the value of entry in (B.18) is monotonically decreasing in φ_s^* and a smaller Λ_s^n implies a greater increase in the value of entry, the productivity cut-off will rise by more in the comparative advantage sector.

Average sector output under costly trade, $q(\tilde{\varphi}_s) = (\tilde{\varphi}_s/\varphi_s^*)^\sigma (\sigma-1) f_s \varphi_s^* + \chi_s (\tilde{\varphi}_{sx}/\varphi_{sx}^*)^\sigma (\sigma-1) f_{sx} \varphi_{sx}^*$, is increasing in average productivity and the productivity cut-off. Thus, relative average output, $\bar{q}_1^n/\bar{q}_2^n$, rises, in the home country, following a reduction in trade barriers. Other things equal, this generates an increase in emissions demand in the home country's comparative advantaged emissions-intense sector, working through the composition effect.

(c) The relative mass of firms, under costly trade, is given by

$$\frac{M_1^n}{M_2^n} = \left(\frac{i^n (1-\beta_2) - \frac{\bar{L^n}}{\bar{K^n}} (\beta_2)}{(\beta_1) \frac{\bar{L^n}}{\bar{K^n}} - i^n (1-\beta_1)}\right) \frac{\left[\left(\frac{\tilde{\varphi}_2^n}{\varphi_2^{n*}}\right)^{\sigma-1} f_2 + \chi_2^n(\varphi_2^{n*}) \left(\frac{\tilde{\varphi}_{2x}^n}{\varphi_{2x}^{n*}}\right)^{\sigma-1} f_{2x}\right]}{\left[\left(\frac{\tilde{\varphi}_1^n}{\varphi_1^{n*}}\right)^{\sigma-1} f_1 + \chi_1^n(\varphi_1^{n*}) \left(\frac{\tilde{\varphi}_{1x}^n}{\varphi_{1x}^{n*}}\right)^{\sigma-1} f_{1x}\right]} \left(\frac{1}{i^n}\right)^{\beta_1-\beta_2} \cdot (1-\theta_1^n) \tag{C.5}$$

Changes in the relative factor prices, driven by converging relative output prices as trade barriers are lowered under costly trade, reveal the role of comparative advantage on the relative mass off firms under costly trade. This can be seen by taking a comparative static of the relative mass of firms with respect to relative factor returns:

$$\begin{aligned}
\frac{\partial\left(\frac{M_1^n}{M_2^n}\right)}{\partial\left(\frac{i^n}{w^n}\right)} = & \underbrace{(i^n)^{\beta_2-\beta_1}\left((1+\beta_2-\beta_1)(1-\beta_2) - \frac{\bar{L^n}}{\bar{K^n}}\frac{(\beta_2)(\beta_2-\beta_1)}{i^n}\right)}_{(+)} \\
& \times \underbrace{\left((\beta_1)\frac{\bar{L^n}}{\bar{K^n}} - i^n(1-\beta_1)\right)^{-1}(1-\theta_1^n)}_{(+)} \\
& + \underbrace{(i)^{\beta_2-\beta_1}\left(i^n(1-\beta_2) - \frac{\bar{L^n}}{\bar{K^n}}(\beta_2)\right)}_{(+)} \\
& \times \underbrace{\left[\left((\beta_1)\frac{\bar{L^n}}{\bar{K^n}} - i^n(1-\beta_1)\right)^{-2}(1-\beta_1)(1-\theta_1^n) + \left((\beta_1)\frac{\bar{L^n}}{\bar{K^n}} - i^n(1-\beta_1)\right)^{-1}\frac{\beta_1}{i^n}(1-\theta_1^n)\right]}_{(+)}
\end{aligned}$$

When environmental policy targets firms' emissions intensities, which translates to holding θ_1 fixed, reducing trade costs raises the relative return of the abundant factor, capital, for the home country, and raises the relative mass of firms in sector 1.

The mass of firms is given by $M_s^n = R_s^n/\bar{r}_s^n$. Under costly trade, the rise in average productivity raises average firm size and thus lowers the mass of firms, other things equal. As noted above, since the rise in productivity is greater in the comparative advantage sector, the fall in the mass of firms is also greater, which will drive down the relative mass of firms, M_1^H/M_2^H, in the home country, and thereby reduce the rise in emissions, other things equal.

Under costly trade, the comparative advantage effect is now dampened due to rising average productivity which raises average firm size by more in the comparative advantage sector thereby reducing the mass of firms more.

Due to consumers elasticity of substitution, $\sigma > 1$ (and thus, $\rho > 1$), the endogenous productivity gains that serve to increase firm size, will dampen, but not reverse, the relative effects of cross-sector resource movement of the composition effect driving changes in the relative mass of firms and raising emissions demand in the home country.

(d) Emissions demand is given by

$$Z_1^n = \frac{\alpha_1 R_1^n}{t^n} = Q_1^n \frac{\alpha_1 P_1^n}{t^n} \tag{C.6}$$

where the aggregate technique effect is captured by $\alpha_1 P_1^n/t^n$. Under costly trade, because of interactions between country-specific changes to relative factor prices, relative output prices, and endogenous productivity changes, the full effect of a trade liberalization on price indices, given by (B.19), cannot be signed analytically in the transition between steady states without additional assumptions regarding the distribution of firm productivity. However, just as in Bernard et al. (2007b), average variety prices are monotonically decreasing in productivity in all sectors and in both countries, and thus the rise in the productivity cut-off, for both the home country and the trading partner, means that prices are declining in productivity following a trade liberalization, other things equal. The rise in the productivity cut-off, and corresponding rise in average productivity in the polluting sector thus generates an endogenous technique effect that lowers emissions, other things equal, even when the country pursues a rigid environmental policy, targeting firm emissions intensities.

This concludes the proof.

Proof of proposition 3 –

From *Proposition 2*, trade liberalization leads to a rise in the productivity cut-off in both sectors. However, due to the greater value of entry in that sector, there is a larger increase in the productivity cut-off, φ_s^{*n}, in the country's comparative advantage sector, which then results in a larger increase in weighted average productivity, $\tilde{\varphi}_s^n$, in the country's comparative advantage sector. Thus, the opening of costly trade results in the emergence of endogenous productivity differences at the sector level, which are positively correlated with Heckscher-Ohlin-based comparative advantage and thus grow as the country's comparative advantage grows.

Appendix D: Tables and Figures

Simulation Results

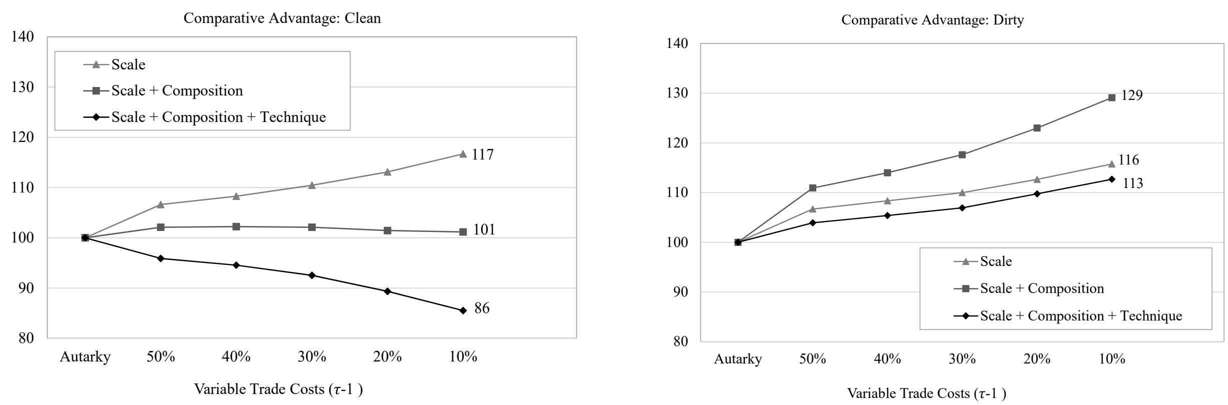

Figure D.1: Combined Framework: Emissions Demand by Channel

Note: This figure presents the evolution of aggregate emissions over time, decomposed into scale, composition, and technique effects, for the home country. The results are based on the combined framework. The three effects are indexed so that they equal 100 under autarky. Changes in each effect are calculated as log-differences in output, market share, and emissions intensity values from those obtained under autarky, using equation (23). In each panel, the home country faces the same environmental regulation as the foreign country ($\theta_1^H = \theta_1^F$). In the left-hand panel, the foreign partner is relatively capital-abundant ($(K/L)^H = 1/(K/L)^F = 1500/1600$), giving the home country a comparative advantage in clean production. In the right-hand panel, these endowments (and thus comparative advantage) are reversed. The left-hand panel shows a +17 percent scale effect, a -16 percent composition effect, a -15 percent technique effect, and an overall decline in emissions of -14 percent. The right-hand panel shows a +16 percent scale effect, a +13 percent composition effect, a -16 percent technique effect, and an overall rise in emissions of +13 percent.

Table 1: Comparison of Heterogeneous and Representative Firm Outcomes

	Rigid Environmental Policy ($(\bar{\theta_1})$)			
	Heterogeneous Firms			Representative Firms
Effect	CA Clean (1)	CA Dirty (2)	No CA (3)	CA Clean (4)
Scale	+16.7	+15.8	+16.0	+15.2
Composition	-15.6	+13.3	0.0	-16.0
Technique	-15.6	-16.4	-16.0	0.0
Total (S+C+T)	-14.5	12.7	0.0	-0.8

Note: This table presents the percent changes (calculated as log-changes) in emissions, for the home country, working through three effects. The Total is the combined scale+composition+technique effect for each model. The first two columns repeat the results shown in the two panels in Figure D.1 when the home country has a comparative advantage (CA) in clean and dirty production (respectively). The third and fourth columns present results from two additional simulations: column (3) adjusts the foreign factor endowments to match those in the home country, and column (4) evaluates the scenario in which the home country holds a relative abundance of labor, but with representative firms (and fixed productivity). In each model, environmental policy targets firm's emissions intensities by fixing θ_1 in the polluting sector. In the representative firm model, as in Copeland and Taylor (2003), this equates to holding the pollution tax measured in terms of the dirty good, t/P_1, constant at its autarky value.

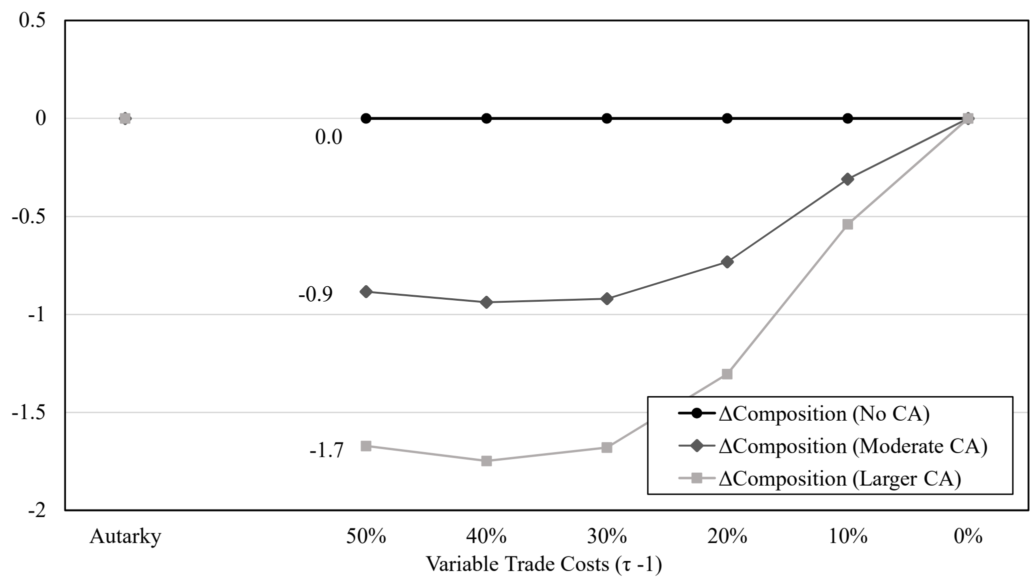

Figure D.2: Difference in Composition Effect with Different Comparative Advantage

Note: This figure presents the percentage-difference, calculated as log-differences and denoted "Δ," between the "Composition" effect obtained in the combined framework and those obtained in a homogeneous-firm model under Autarky and for tariffs ranging from 50 percent to 0 percent. Each line shows this difference for a different set of factor endowments that change the country's comparative advantage. The homogeneous-firm model is calibrated to generate the same outcomes as the heterogeneous-firm model under autarky. In the first case, both the relative endowments and the environmental stringency in the two countries is the same. In the second case, the relative abundance of capital is raised, and in the third case, it is raised further. Thus, for example, for a 50 percent tariff, the combined framework predicts an increase in emissions demand, due to the composition effect, that is 0.9 percent lower than that predicted in a homogeneous-firm framework, but predicts that moderating effect will rise as the country's comparative advantage rises, predicting emissions growth that is 1.7 percent lower when the country's endowments, and thus comparative advantage, more strongly diverge.

Table 2: 3 Shocks in the Combined Framework

	Scenario	K^H	L^H	k^F	l^F	θ^H	θ^F	τ	$\frac{K^H/L^H}{k^F/l^F}$
0	Baseline	1,630	1,500	1,500	1,630	0.035	0.01	3.5%	1.18
1	Trade Liberalization	1,630	1,500	1,500	1,630	0.035	0.01	**45%**	1.18
2	+ Increased Environmental Stringency	1,630	1,500	1,500	1,630	**0.0319**	0.01	45%	1.18
3	+ Factor Expansion	**1,608**	**1,243**	**1,243**	**1,608**	**0.0322**	0.01	**44.9%**	**1.67**

Note: This table details the three shocks that are evaluated in the combined framework. Values in bold font denote the changes made in moving from one scenario to the next. In Scenario 1, the model simulates the response to a decline in trade costs from 45 percent to 3.5 percent. Scenario 2 simulates a roughly 10 percent increase in home environmental stringency, and scenario 3 simulates outcomes associated with a relative increase in factors favoring clean production at home (roughly 20 percent labor expansion and 1 percent capital expansion), and slight adjustment to trade costs and regulatory stringency. In each of the three scenarios, the home country maintains a comparative advantage in dirty production ($P_1^H/P_2^H < P_1^F/P_2^F$).

Table 3: Outcomes from 3 Shocks in the Combined Framework

	Scenario	Imports	Output	Market Share (dirty sector)	Emissions Intensity	Total Emissions
0	Baseline	1,541	20,466	0.51	0.0061	64.30
1	Trade Liberalization	727	18,251	0.50	0.0069	62.32
2	+ Increased Environmental Stringency	725	18,288	0.50	0.0091	83.73
3	+ Factor Expansion	726	16,027	0.58	0.0090	84.05

Note: This table contains the raw numerical outcomes associated with each of three shocks that are evaluated in the combined framework. Each scenario corresponds to one shock to the economic framework, detailed in Table 2.

Table 4: 3 Shocks and 3 Effects in the Combined Framework

Scenario		Imports	Scale	Composition	Technique	Total
0	Baseline	100%	100%	100%	100%	100%
1	Trade Liberalization	**212%**	111%	**103%**	89%	103%
2	+ Increased Environmental Stringency	**213%**	111%	102%	**60%**	**74%**
3	+ Factor Expansion	**212%**	**124%**	**88%**	**61%**	**73%**
	Levinson (2009)	+112%	+24%	+3% / -12%	-39%	-27%

Note: This table details the percent increase in imports ($Imports_{Baseline}/Imports_1$, etc.), as well as the scale, composition, and technique effects, that result from each of three shocks detailed in Table 2. The scale, composition, and technique effects are calculated as log-changes, ensuring that the sum of all changes equals the total change in emissions. A trade liberalization, alone, generates a +11 percent increase due to a scale effect, a +3 percent composition effect, and a -11 percent technique effect, thus generating an overall increase of +3 percent. The final line reports the results of each channel documented by Levinson (2009). Values in bold denote outcomes within one percentage point of those documented by Levinson (2009).

Table 5: Relative Importance of Shocks in the Combined Framework

Scenario Shock:	Trade Liberalization (1)	Environmental Stringency (2)	Factor Expansion (3)	Total (Effects)
Effect:				
Scale	+11.5	-0.3	+13.1	+24.3
Composition	+3.0	-0.6	-14.6	-12.2
Technique	-11.4	-25.9	-1.6	-38.9
Total (Shocks)	+3.1	-26.8	-3.1	-26.8

Note: This table details the *ceteris paribus* contribution of each shock (detailed in Table 2) to each of the scale, composition, and technique effects, as well as to total emissions. The total of each effect, as well as the total change, is equal to the corresponding value documented in Table 4.

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