Regional Heterogeneity in Environmental Quality: The Role of Firm Production Networks and Trade

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November, 2023

Abstract

We study how globalization shapes regional environmental accounts by developing a general equilibrium model capturing the effect of trade liberalization on the spatial distribution of firms and regional disparities in environmental quality within countries in a setting of multi-stage firm-to-firm trade. Reductions in trade costs cause more firms to collocate in regions with better access to foreign markets. Consequently, more pollution is generated in such regions while spatial selection and outsourcing activities through endogenously established production networks lower these regions' emission intensities. Additionally, we establish that reductions in international trade costs give rise to a positive environmental spatial spillover effect mediated through networks, which reduces disparities in emission intensities between regions with differential access to foreign markets. Our findings thus highlight the role of supply networks between firms as a key factor linking globalization and differences in regional environmental quality.

JEL Codes: F18, F64, Q53, R11, R12
Keywords: Regional Environmental Quality, Firm-to-Firm Production Networks, Globalization

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* The views, opinions and/or findings contained in this paper are those of the authors and not those of The MITRE Corporation or its government partners. PRS Release Number: 20-2177.

1 Introduction

Environmental data describe that regions with relative proximity to foreign markets tend to at once exhibit higher levels of air pollution, but lower emissions intensities.[1] While this phenomenon is conceivably attributable to a host of factors, such as differences in industrial composition, regional features, or regulatory environments, recent work also increasingly highlights the prominent role played by firms' offshoring and outsourcing decisions in shaping environmental outcomes (see, e.g., Cole et al. 2014, 2021). However, there remains a notable gap in the understanding of how globalization and the evolving geography of trade and production, particularly through multi-stage production networks linking firms, interact to determine regional differences in environmental quality.

We address this research gap by theoretically modeling the relationship between market access, the location of economic activity, and regional pollution disparities in a general equilibrium framework. We specifically focus on identifying how firm production networks influence regional differences in emissions and emission intensities in open economies with active environmental policies. Our model additionally incorporates firms' endogenous decisions toward abatement investment and outsourcing of production inputs, taking into account their ability to optimally establish production relationships with other firms. Furthermore, we examine how the geographical distribution of firms adjusts in response to changes in foreign market access. We also conduct a series of numerical counterfactual experiments to directly quantify how trade costs determine the spatial sorting of firms, and consequently, regional emissions and emissions intensities. Ultimately, we illustrate how globalization drives regional disparities in environmental quality.

Our model captures three important stylized observations. First, firms tend to concentrate in regions that offer the best access to foreign markets (Guo, 2017). Second, the regions offering better accessibility to foreign demand exhibit greater emissions but lower emission per unit of economic outputs compared to those facing higher international trade costs. Lastly, firms are increasingly connected through multi-stage production networks, which allows them to reduce their emissions by outsourcing production to other firms via intermediate input trade. Our model incorporates these features in an analytical framework which assumes homogeneous environmental regulations across regions and countries in order to isolate the effect of firm-to-firm production networks on variation in firm-level and regional environmental accounts.

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[1] Defined as the emissions of a particular pollutant per unit of economic output.

Our analysis yields three main findings. We first establish a positive analytical relationship between network density (the intensity with which firms establish supply relationships with one another), abatement investments, and total emissions. The logic behind this result relates to the idea that, when network participants are able to obtain production factors at a lower price from a large number of supplier firms and sell outputs to a wider array of customer firms, firm-level emissions increase due to the expanded scale of production activities. When pollution generated from production causes firms to incur a regulatory cost, this scale effect encourages firms to invest in abatement in order to reduce their emissions tax payments. At the same time, robust supply networks raise firms' profit margins, allowing them to bear greater abatement costs.

Second, we document a negative relationship between network density and emission intensities. Robust supply relationships between firms facilitate the replacement of emission-intensive inputs with outsourced intermediate goods. This enables larger, more efficient firms to lower their emission intensities because their outsourcing activities significantly constrain the increase in their total emissions arising from expanded production. Smaller, less efficient firms tend to exhibit greater emission intensities compared to larger firms. Because of the limited scope of the production networks maintained by smaller firms, outsourcing is less viable, and investing in abatement serves as the main channel through which total emissions can be reduced.

Third, we demonstrate that globalization and firm-to-firm linkages are important in determining economic geography. Trade cost reductions incentivize larger, more productive firms (which, following Melitz 2003, are the ones most likely to engage in international trade) to collocate within regions that afford the best access to foreign markets and increases the likelihood of establishing supplier relationships with foreign firms. The existence of firm-to-firm networks intensifies this collocational force by encouraging smaller firms to locate with larger firms such that the benefits from domestic inter-firm trade can be maximized. As a result, the number of firms located in such regions rises, and the density of firm-to-firm production networks increases in response to globalization.

This paper contributes to several strands of literature. First, our study is inspired by a number of closely related prior works on production networks and the spatial sorting of firms. In this vein, Guo (2017) explores the role of trade cost reductions on firms' agglomeration toward China's coastal provinces, and empirically documents that the country's accession to the World Trade Organization (WTO) caused the number of firms in coastal provinces to increase.[2] Work by Lim (2017) estab-

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[2] Nagy (2023) also considers the role of international trade and spatial frictions on the location and formation of

lishes a theoretical foundation for these empirical findings by characterizing how the endogenous formation of firm-to-firm networks shapes intermediate trade between firms. Importantly for our own results, Lim shows that large and efficient firms are better able to establish relationships with other firms owing to larger expected profits that can be realized from participation in supplier networks. Miyauchi (2019) helps bridge these two studies by showing that production networks between firms are an important determinant of firms' agglomeration.[3] We extend this literature on endogenous production networks and the spatial sorting of firms to study the implications of these mechanisms for regional disparities in environmental quality.

Second, our paper contributes to the literature that studies the environmental consequences of globalization in a setting with heterogeneous firms.[4] Previous work has demonstrated that one of the channels through which trade liberalization can improve environmental quality is through the exit of the least productive firms due to increased competition. This leads to the reallocation of market share to the most efficient firms: a so-called market share reallocation effect.[5] We also capture these effects by assuming that firms incur costs to establish and sustain supplier relationships with other firms, relationships which are fundamentally related to the size of international trade costs. This setup enables us to not only depict the market share reallocation effect of globalization via firm exits, but also demonstrates the role of intermediate input outsourcing in this process. We formally investigate this mechanism as one of the channels through which globalization influences environmental quality, a feature absent from much of the existing literature.

Third, our study extends the literature on firms' decisions with regard to the optimal level of

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cities. Baldwin and Okubo (2005), Okubo (2009), and Okubo et al. (2010) combine Melitz-type heterogeneous firm models with the new economic geography framework established in Krugman (1991) to theoretically demonstrate that firm relocations are more likely to take place for relatively large and productive firms, a spatial selection effect. Work by Ottaviano (2010) and von Ehrlich and Seidel (2013) is in line with this literature, but these studies analyze the agglomeration of firms occurring through the entry and exit of firms, rather than via the relocation of firms. Our model incorporates both the entry/exit problem of firms and their spatial sorting by accounting for the heterogeneous features of firms' networks.

[3] Miyauchi demonstrates that downstream (i.e., input-demanding) firms exhibit higher revenues when locating where upstream (i.e., input-supplying) firms are dense as they are more likely to be matched with suppliers. This creates a positive feedback for the supplying firms. Put differently, a larger market incentivizes upstream firms to agglomerate in the location where they expect a higher matching rate with customers.

[4] See, for example, Baldwin and Ravetti (2014); Kreickemeier and Richter (2014); Konishi and Tarui (2015) and Barrows and Ollivier (2018).

[5] Besides "composition effects', which reflect changes in emissions resulting from structural changes away from or toward emissions-intensive industries or activities (Copeland and Taylor, 1994; Cherniwchan et al., 2017), "technique effects" (the use of less emissions-intensive production processes) have been extensively explored. For example, Antweiler et al. (2001), Levinson (2009), Grether et al. (2009) and Shapiro and Walker (2018) argue that the openness of an economy plays little role in determining emission intensities, asserting instead that recently observed country- and industry-level improvements in air quality can mainly be attributed to technique effects originating from stricter environmental regulations. To abstract from the effects of environmental policy in determining regional environmental quality, we will assume in our modeling framework that regulatory regimes are the same across regions.

abatement investment as a means to minimize emission tax payments (Shapiro and Walker, 2018; Gutiérrez and Teshima, 2018; Forslid et al., 2018). Our work differs from the earlier literature in considering the abatement investments of firms in the context of production networks. We find that larger and more productive firms invest in abatement more intensively than their smaller, less efficient counterparts, because larger firms are better able to afford the cost of abatement investments. However, the existence of firm-to-firm linkages enables larger firms to reduce their abatement expenditures in favor of outsourcing intermediate production. In other words, outsourcing activities serve a fundamental role in constraining the increase of firms' total emissions alongside the role played by abatement investments.

Fourth and finally, our work builds on the body of research investigating how globalization and outsourcing affect environmental quality. A number of past studies have shown that outsourcing intermediate production from abroad effectively reduces firms' emission intensities, total emissions, and abatement expenditures (Li and Zhou, 2017; Cole et al., 2021). However, the outsourcing behaviors of firms in this context are mainly determined by differences in environmental regulations across countries as firms outsource intermediate production to foreign markets with relatively lax environmental policies (i.e., pollution haven effects). In contrast, we show that outsourcing takes place even when environmental regulations are uniform across countries and domestic regions when firms are able to optimally establish relational production networks.

Additionally, and in contrast with previous studies examining related questions, our focus centers on analyzing regional variation in environmental accounts within a country. As we will demonstrate, the role of firm-to-firm production networks in linking globalization with regional environmental outcomes plays a pivotal role in this setting. For instance, when trade barriers fall, it becomes possible for more emission-intensive firms to outsource their polluting in-house production by forming networks with efficient firms located outside their region. Our model captures this aspect of negative assortative matching between firms, and accounts for the fact that regions hosting smaller and less efficient (and more polluting) firms can benefit from positive environmental spatial spillover effects mediated by firm-to-firm networks, thereby reducing disparities in regional environmental conditions.

The remainder of the paper is organized as follows. Section 2 establishes three stylized facts relating to economic geography and regional disparities in environmental accounts across US states. Motivated by this, Section 3 develops our theoretical model that analyzes the role of production networks and the spatial sorting of firms in determining regional disparities in environmental quality. In Section 4, we undertake numerical simulations to quantify the analytical findings from Section 3. Finally, Section 5 provides concluding discussion.

2 Stylized Facts

We highlight three stylized facts relating to regional differences in emissions and economic activity that illustrate the role of production networks in influencing inter-regional environmental outcomes. We first define the terminologies that we will use throughout the paper to distinguish types of regions. We refer to *core* regions as areas with the easiest access to foreign markets, i.e., for which international trade costs are lowest. In contrast, *periphery* regions are those that face comparatively higher barriers to trade with foreign markets.[6] As a result, more economic activity tends to concentrate in the former over the latter, which coincides with a larger number of firms (and establishments) agglomerating in core regions.

We preface our discussion by noting two important details. First, while our analysis emphasizes the role of market access and endogenous production networks in shaping spatial disparities in environmental quality, we readily acknowledge the relevance of other channels by which regions' environmental accounts are determined: among others, heterogeneous regulatory environments or differences in industrial composition. Rather than downplaying the importance of these other factors, our analysis aims to complement these well-known channels by investigating the role of endogenous production networks in explaining regional disparities in environmental quality, a relationship which to date has remained mostly unexplored in the literature. Second, as our primary focus is to analytically characterize the relationship between production networks, market access, and regional environmental quality, the supporting evidence that we present in this section is largely correlational; consequently, we leave formal empirical analyses of causality for future work.

With this in mind, we present the following stylized facts that characterize the distribution of air pollution and economic activity across core versus periphery regions (explicit quantitative definitions for which we provide below) in the United States:[7]

1. Firms and establishments tend to locate more in core regions than periphery regions.
2. More industrial emissions are generated in core regions compared to periphery regions;

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[6] We use this designation primarily to reflect the foreign trade costs faced by regions rather than regions' geographical characteristics, while noting that geography is a fundamental determinant of proximity to foreign markets.

[7] We also examine evidence for Chinese provinces to assess the generalizability of these relationships; see Appendix A in the Online Appendix.

however, core regions typically exhibit lower emission intensities than periphery regions.

3. Core regions are typically net importers of intermediate inputs from both domestic and foreign sources and host a larger number of inter-firm supply networks.

As each of these empirical regularities hinge on locations' status as core regions, access to foreign markets plays a fundamental role in mediating regional disparities in environmental quality. Our model incorporates each of these features to analyze the production-network-based mechanism that drives higher emissions but lower emission intensities in core regions relative to periphery regions, particularly in relation to emissions embodied in traded intermediates.

Measure of Foreign Market Access To construct a quantitative measure of individual US states' average level of foreign market access for descriptive purposes, we compute the well-known Head-Ries Index (denoted HRI; from Head and Ries, 2001) for each of the 48 contiguous US states and for the top 10 US trade partners in terms of total two-way manufacturing trade for 2017.[8] The HRI has been extensively used as a theory-consistent measure of trade costs and market integration (see, e.g., Jacks et al., 2008, Eaton et al., 2016, and Cherniwchan, 2017). The bilateral HRI is calculated for each state i and foreign trading partner j as

$$HRI_{ij} = \sqrt{\frac{X_{ij}}{X_{jj}}\frac{X_{ji}}{X_{ii}}},$$

where X_{ij} is the value of exports from i to j and X_{ji} is the value of exports from j to i. X_{ii} and X_{jj} give the values of *intra*-region trade for i and j, which we compute as domestic sales, i.e., the residual of total manufacturing production and total manufacturing exports.[9] In essence, the HRI measures the degree of market integration between any two trade partners as the geometric mean of the ratios of foreign consumption relative to own-consumption for both sides in the trading relationship. Its values are inversely related with the level of bilateral trade frictions, i.e., larger values of HRI imply lower trade costs between i and j.

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[8] We exclude petroleum and coal products manufacturing in order to focus on non-energy manufacturing sectors. The 10 US trade partners considered in this analysis are, in order of total trade with the United States, Canada, China, France, Germany, India, Japan, South Korea, Mexico, Taiwan, and the United Kingdom.

[9] Data on international trade (X_{ij} and X_{ji}) are obtained from the US Census Bureau, which reports states' bilateral exports and imports in manufacturing by NAICS industry. Intra-state trade (X_{ii}) is computed as the residual of each state's total manufacturing production (data from US Bureau of Economic Analysis) and exports to the rest of the world (data from US Census Bureau). Both calculations exclude NAICS industry 324 – Petroleum and Coal Manufacturing. We similarly calculate intra-country trade (X_{jj}) for each of the foreign trade partners in the analysis based on data for non-energy manufacturing sectors from the 2021 version of the OECD's Trade in Value Added (TiVA) database, which records gross output and foreign exports by country and sector.

To account for country-specific determinants of trade costs, we normalize these values by dividing them by the average value of HRI_{ij} for each foreign trading partner (i.e., $\frac{1}{48}\sum_i HRI_{ij}$ for each foreign partner j). Finally, to obtain a single measure of states' multilateral foreign market access, we take the simple average of these normalized values across the 10 foreign trading partners:

$$\overline{HRI}_i = \frac{1}{10}\sum_j \left(\frac{HRI_{ij}}{\frac{1}{48}\sum_i HRI_{ij}} \right).$$

As with the bilateral expression for HRI, larger values of the multilateral trade cost measure $\overline{HRI}_i$ correspond to regions which face lower average foreign trade costs. For descriptive purposes, we categorize states as core regions if $\overline{HRI}_i$ is at or above the 75th percentile of the index's sample distribution, and classify all other states as periphery regions.[10]

Stylized Fact 1: Market Access and the Spatial Agglomeration of Firms We first present evidence on the number of establishments (of all sizes) in non-energy-intensive manufacturing industries across US states from the US Census Bureau's 2017 Statistics of US Businesses (SUSB) to investigate the relationship between foreign market access and economic geography.[11] Figure 1 reveals a close relationship (correlation $R = 0.81$) between the ranking of states by their calculated values of HRI and the ranking of states in terms of number of establishments, supporting the assertion that firms tend to collocate in regions with the best access to foreign markets. More specifically, our data reflect that around 57 percent of total manufacturing establishments are located within the 12 identified core states.[12] Taken together, these observations provide strong support for the notion that firms tend to agglomerate in regions with the best access to foreign markets.

Stylized Fact 2: Market Access and Regional Environmental Accounts We next describe the heterogeneous regional distribution of emissions and emission intensities for selected local pollutants. Panels (a), (b), and (c) of Figure 2 respectively present the relationship between

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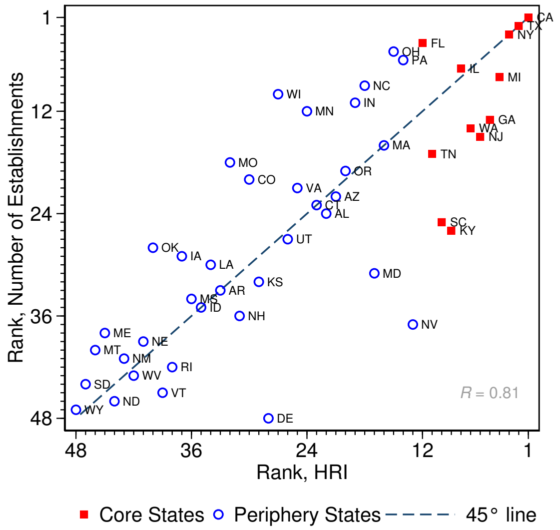
[10] Using this definition, we identify 12 states as core regions: California ($\overline{HRI}_i = 4.7$), Texas (3.5), New York (2.5), Michigan (1.9), Georgia (1.9), New Jersey (1.9), Washington (1.8), Illinois (1.8), Kentucky (1.6), South Carolina (1.6), Tennessee (1.5), and Florida (1.4).

[11] We consider establishments (rather than firms as in our theoretical model) for descriptive purposes in order to appropriately capture the physical location of firms, as some firms maintain headquarters in separate locations from their establishment(s). However, firms and establishments are generally synonymous, and the spatial distribution of establishments largely overlaps with the spatial distribution of firms. We exclude establishments in the 3-digit NAICS industries Food (311), Primary Metals (331), Paper (322), Petroleum and Coal Products (324) and Chemicals (325) sectors which were the five largest energy-consuming industries according to data for 2018 from the Energy Information Administration's (EIA) Manufacturing Energy Consumption Survey (MECS) database.

[12] When using the sample average value of $\overline{HRI}_i$ as the threshold for classifying core and periphery regions, we find that the proportion of establishments located in core states rises to 72 percent.

Figure 1: Distribution of US Establishments and States' Foreign Market Access



Notes: Data on establishment counts in manufacturing (NAICS codes 31–33) are from the US Census Bureau's 2017 Statistics of US Businesses (SUSB). Energy-intensive manufacturing industries in terms of total first use of energy for all purposes are excluded in calculating the number of establishments. Core versus periphery regions are categorized as those with values of $\overline{HRI}_i$ above or below its 75th percentile value, respectively.

states' total industrial emissions (in logs) of carbon monoxide (CO), fine particulates ($PM_{2.5}$), and nitrogen oxides (NO_x) in non-energy-intensive manufacturing industries and values of HRI, while panels (d), (e), and (f) show the corresponding relationship between emission intensities (also in logs) and HRI.[13] Each subfigure also includes the estimates of the univariate regression equation and correlation coefficient corresponding to these relationships. The contrasting patterns in total emissions and emission intensity between core and periphery regions can be readily verified. Panels (a)–(c) portray a systematic positive correlation between states' HRI values and total emissions for each of the depicted pollutants, suggesting that more pollution is generated in core versus periphery regions. In contrast, panels (d)–(f) illustrate a systematic negative correlation between HRI and emission intensity, suggesting that production in core regions typically generates lower emissions per unit of output.[14]

The collocation of establishments explains, at least in part, the fact of greater total emissions in core regions compared to periphery regions; however, it does little to explain the fact of lower emission intensities in core regions. A number of factors, such as differences in regulatory regimes and

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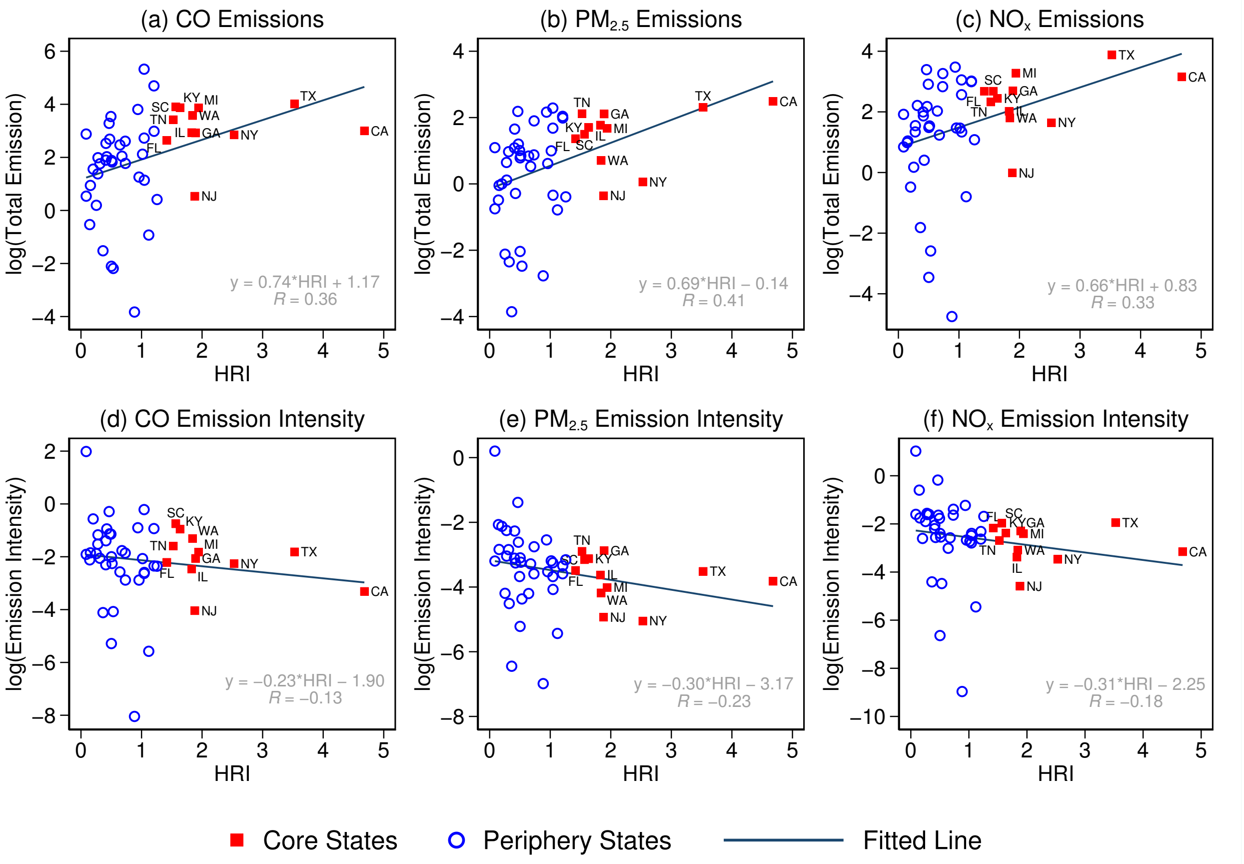
[13] We present similar evidence on the distribution of other local pollutants including particulate matter (PM_{10}), sulfur dioxide (SO_2), and ammonia (NH_3) across US states in Online Appendix B.

[14] The correlation between emissions (emission intensity) in levels and HRI are 0.246 (–0.170) for CO, 0.573 (–0.214) for $PM_{2.5}$, and 0.498 (–0.228) for NO_x.

Figure 2: Correlation between Foreign Market Access and Regional Environmental Accounts

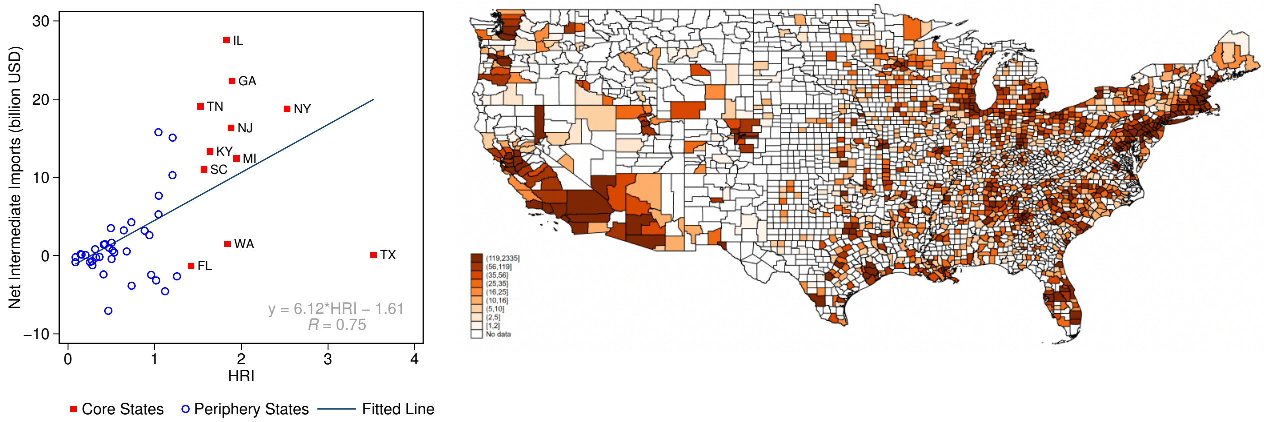


Notes: Emissions are measured in thousand tons and emission intensity is measured as thousand tons of emissions per billion dollars of gross output in non-energy manufacturing. Emissions data are from the 2017 version of the National Emission Inventory (NEI) overseen by the US Environmental Protection Agency (EPA). Gross output is based on data from the US Bureau of Economic Analysis (BEA). Environmental accounts are log-transformed due to outliers in levels.

industrial mixes or firm selection and composition effects might drive this observation. Therefore, we next characterize a channel through which firms in core areas are able to constrain or reduce their total emissions via the establishment of relational supply networks, which we assert accounts in part for the observed regional disparities in emissions intensities.

Stylized Fact 3: Market Access, Intermediate Trade, and Relational Supply Networks To analyze the origins of the observed spatial disparities in emission intensities between core and periphery regions as they relate to trade in intermediates, we consider the patterns of intermediate goods trade (as a measure of outsourcing activities) and the prevalence of relational supply chains with foreign establishments (as a measure of firms' participation in global production networks) for core versus periphery US regions. Existing empirical work supports the notion that outsourcing

Figure 3: Regional Heterogeneity in Establishment-level Networks and State-level Commodity Flow


(a) Intermediate Imports and HRI, by State

(b) Relational Supply Chains with Foreign Partners

Notes: Panel (a) portrays states' net foreign imports (in billion USD) based on data from the US Census Bureau. California is omitted as an outlier for display purposes. Intermediate goods encompass the BEC product groupings "Industrial supplies, n.e.s." (BEC-2) and "Capital goods (except transport equipment), and parts and accessories thereof" (BEC-4). Panel (b) (adapted from Choi et al. 2023) shows the total number of relational supply chains with foreign suppliers and customers maintained by establishments within each county based on data from FactSet Revere.

(both domestic and foreign) is associated with lower emission intensities of firms, implying that the extent to which firms are able to source inputs from suppliers in other regions is an important determinant of regional environmental accounts.[15]

To document the extent of outsourcing in core versus periphery regions, and thus the scope for the outsourcing of emissions, panel (a) of Figure 3 depicts the value of states' net foreign imports of intermediate goods based on US Census Bureau data for 2017 (California is omitted as a visual outlier, though this exclusion does not meaningfully alter the observed relationship).[16] Apparent is a strong positive association ($R = 0.75$) between net intermediate imports and foreign market accessibility (HRI). Although not directly observable, the net inflow of intermediate goods in core regions is consistent with the outsourcing of (embodied) pollution because sourcing these goods locally would have otherwise generated pollution within the sourcing region.

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[15] Along these lines, Feng et al. (2013) offer evidence that firms in China's coastal (core) provinces "outsource" their emissions to firms in inland (periphery) regions via CO_2 embodied in emission-intensive inputs sourced from inland firms. In addition, they show that globalization intensified flows of CO_2 embodied in inputs as rising exposure to trade caused an increase in demand for intermediates from inland firms by coastal Chinese exporting firms. Li and Zhou (2017) document a negative relationship between foreign outsourcing of emission-intensive inputs by US manufacturing firms and releases of toxic material by US plants. Cole et al. (2021) find that foreign outsourcing activities by Japanese firms on average reduce the growth of firms' CO_2 emission intensity by 7.3%p–7.7%p compared to non-outsourcing firms.

[16] We define intermediate goods here as products belonging to the Broad Economic Category (BEC) groups "Industrial supplies, n.e.s." (BEC-2) and "Capital goods (except transport equipment), and parts and accessories thereof" (BEC-4).

To complement the information provided in panel (a), panel (b) (excerpted from Choi et al. 2023) depicts the total number of US establishments' supplier and customer relationships with foreign establishments as derived from the FactSet Revere firm-level dataset. The figure makes clear that relational supply networks tend to be denser in most coastal (core) regions of the US, implying that the scope for firms to establish firm-to-firm networks is greater in such regions by virtue of their relative proximity to foreign markets. In line with panel (a), this observation is consistent with firms in core regions being able to engage more intensively in outsourcing production inputs, and thereby maintain lower emission intensities via the outsourcing of pollution to the input-supplying regions.

Guided by these stylized facts, in the following analysis we develop an analytical framework with which to model the role of the spatial sorting of firms and firm-to-firm supply networks in shaping regional disparities in environmental accounts.

3 Conceptual Framework

To examine the relationship between globalization and regional environmental disparities, we propose a general equilibrium model that focuses on the formation of optimal relational production networks between firms (i.e., the endogenous production networks). While our analytical framework builds upon that of Lim (2017), we extend his approach by incorporating several key factors. First, we explore how firms endogenously engage in domestic and international outsourcing of intermediate inputs. Second, we examine how firms make optimal decisions regarding investment in air pollution abatement in response to environmental regulations. Lastly, we investigate the impact of international trade cost reductions on the spatial distribution of firms, specifically exploring the role of firm-to-firm networks in shaping this distribution across core versus periphery regions.

3.1 Basic Environment

We assume the economy consists of households and monopolistically competitive firms. We denote the set of firms as S_χ, and each firm is characterized by its fundamental characteristics, denoted as χ. These characteristics include the firm's productivity in using emissions-producing inputs (ϕ) and the demand for the firm's specific variety of output (δ), which influences the firm's size in terms of total sales. The firm's characteristics, i.e., $\chi = (\phi, \delta)$, are randomly drawn from a cumulative distribution function G_χ with density g_χ.[17]

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[17] Our baseline model abstracts from labor and labor mobility because our objective is to isolate the role of firms' spatial sorting in response to changes in trade costs in shaping regional environmental accounts while holding fixed the role of other factors. However, in Online Appendix C we present an extended version of our model in which (i) labor is mobile

3.1.1 Households

We assume that the representative household exhibits CES preferences over all available varieties:

$$U = \left[\int_{S_\chi} \left[\delta x_H(\chi) \right]^{\frac{\sigma-1}{\sigma}} dG_\chi\left(\chi\right) \right]^{\frac{\sigma}{\sigma-1}}, \tag{1}$$

where σ is the elasticity of substitution between differentiated outputs, and $x_H\left(\chi\right)$ is the household's consumption of each variety. Given the price of firm χ's variety, $p_H\left(\chi\right)$, the optimal household demand is

$$x_H\left(\chi\right) = \Delta_H \delta^{\sigma-1} p_H\left(\chi\right)^{-\sigma}, \tag{2}$$

where $\Delta_H \equiv U P_H^{\sigma}$ is common across all varieties with the consumer price index given by

$$P_H \equiv \left[\int_{S_\chi} \left(\frac{p_H(\chi)}{\delta} \right)^{1-\sigma} dG_\chi(\chi) \right]^{\frac{1}{1-\sigma}}. \tag{3}$$

3.1.2 Firm Production Technology

To produce, firms use both emission-producing inputs (e.g., heat inputs from burning fossil fuels), denoted as $z(\chi)$ and which we henceforth describe as "dirty inputs," and intermediates obtained from upstream firms χ', denoted as $x(\chi, \chi')$. All firms face an identical constant elasticity of substitution (CES) production technology, capturing the trade-off between dirty and intermediate inputs.

Outsourcing inputs takes place under uncertainty since supplier-consumer relationships are established non-deterministically. Firm χ can only purchase inputs from supplier firm χ' with probability $m\left(\chi, \chi'\right)$. Given the uncertainty in matching, we introduce a CES output production function for firm χ as

$$X(\chi) = \left[\left[\phi z(\chi) \right]^{\frac{\sigma-1}{\sigma}} + \int_{S_\chi} m(\chi, \chi') \left[x(\chi, \chi') \right]^{\frac{\sigma-1}{\sigma}} dG_\chi(\chi') \right]^{\frac{\sigma}{\sigma-1}}. \tag{4}$$

As local air pollutants are, to a large extent, generated from the combustion of fossil fuels in manufacturing industries (Copeland et al., 2021) we assume that firm χ's emissions, e, are proportional to the firm's use of dirty inputs. Moreover, we assume that emissions can be monotonically reduced

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and endogenously allocated by households across regions within countries, and (ii) households receive disutility from congestion costs generated by the crowding of scarce regional amenities. The results of this extended model largely mirror those of our baseline analysis.

by abatement investments, $\mathcal{A}(\chi)$, for example, the installation of scrubbers or filters to capture end-of-pipe pollution:[18]

$$e(\chi) = \frac{\epsilon z(\chi)}{\mathcal{A}(\chi)}. \tag{5}$$

The scale parameter $\epsilon > 0$ determines the size of the marginal effect from the use of dirty inputs on emissions.

The effective price of dirty inputs, $\kappa(\chi)$, consists of the unit price of the dirty input, ω, and the cost of a per-unit emission tax t levied on the pollution generated from the use of the dirty input:[19]

$$\kappa(\chi) = \omega + \frac{te(\chi)}{z(\chi)}. \tag{6}$$

Given input prices and abatement investment, the cost-minimization problem of firm χ yields the marginal cost of production $\eta(\chi)$, the optimal levels of dirty inputs, $z(\chi)$, and the intermediates sourced from supplier firm χ', $x(\chi,\chi')$, specifically as:

$$\eta(\chi) = \left[\phi^{\sigma-1}\kappa(\chi)^{1-\sigma} + \int_{S_\chi} m(\chi,\chi')p(\chi,\chi')^{1-\sigma} dG_\chi(\chi')\right]^{\frac{1}{1-\sigma}}, \tag{7}$$

$$z(\chi) = X(\chi)\eta(\chi)^{\sigma}\kappa(\chi)^{-\sigma}\phi^{\sigma-1}, \tag{8}$$

$$x(\chi,\chi') = X(\chi)\eta(\chi)^{\sigma}p(\chi,\chi')^{-\sigma}, \tag{9}$$

where $p(\chi,\chi')$ is the unit price of intermediate inputs charged by the supplier firm χ'. Firms determine the prices of their intermediate outputs in a way that maximizes their profits. We assume the market is monopolistically competitive which leads to the standard markups over marginal cost:

$$p_H(\chi) = p(\chi',\chi) = \mu\eta(\chi), \tag{10}$$

where $\mu = \frac{\sigma}{\sigma-1}$.

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[18] We can further generalize the pollution generation process by assuming concavity of the emissions function reflecting diminishing marginal environmental damages. The results are qualitatively unchanged under this additional assumption.

[19] Although we do not explicitly consider the redistribution of tax revenue, the key predictions of our model do not change if we assume that the tax revenue is disbursed to the representative household in a lump-sum manner. Lim (2022) and Shapiro and Walker (2018) simply assume that tax revenues are lost due to rent-seeking. Also note that the unit cost of the dirty input varies by firm only because of size of firms' emissions tax payments, which varies across firm.

3.1.3 Market Clearing and the Optimal Pricing Strategy

The optimal demands for dirty inputs and intermediate varieties lead to the following market clearing conditions:

$$Z = \int_{S_\chi} z(\chi) dG_\chi(\chi), \tag{11}$$

$$X(\chi) = x_H(\chi) + \int_{S_\chi} m(\chi', \chi) x(\chi', \chi) dG_\chi(\chi'), \tag{12}$$

which describe that the total supply (endowment) of dirty inputs, Z, is equal to the sum of total demand for the dirty input. In addition, the total production of firm χ, $X(\chi)$, is equal to the sum of household demand and each firm's demand for firm χ's variety.[20]

3.2 Equilibrium of the Model

3.2.1 The Characteristics of a Firm's Network

We next introduce two concepts from Lim (2017): the so-called *network demand*, $\Delta(\chi)$, and the *network productivity*, $\Phi(\chi)$, which are functions of firms' fundamental features:

$$\Delta(\chi) \equiv \frac{1}{\Delta_H} X(\chi) \eta(\chi)^\sigma, \tag{13}$$

$$\Phi(\chi) \equiv \eta(\chi)^{1-\sigma}. \tag{14}$$

The network demand of firm χ represents the value of intermediate outputs used by downstream (customer) firms in the network relative to that consumed by the representative household. The network productivity is determined by the inverse measure of marginal production cost, meaning that the network efficiency of firm χ increases when it can obtain intermediate inputs from other firms (and/or the dirty input) at lower prices.

Based on the optimal factor demands, market clearing, and the definition of network characteristics, we derive the following expressions for network demand and network productivity:

$$\Delta(\chi) = \mu^{-\sigma} \delta^{\sigma-1} + \mu^{-\sigma} \int_{S_\chi} m(\chi', \chi) \Delta(\chi') dG_\chi(\chi'), \tag{15}$$

$$\Phi(\chi) = \phi^{\sigma-1} \kappa(\chi)^{1-\sigma} + \mu^{1-\sigma} \int_{S_\chi} m(\chi, \chi') \Phi(\chi') dG_\chi(\chi'). \tag{16}$$

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[20] Following Lim (2022), we assume that output varieties are distributed among households and firms. This means that the varieties consumed by households are treated as final goods, while the varieties demanded by firms are considered intermediates.

Equation (15) shows that the network demand of supplier firm χ depends on the fundamental demand it faces and the network demands of its customer firms. This means that a firm can increase its network demand by forming relationships with more and larger customer firms. Equation (16) has a similar interpretation. The network productivity of firm χ is determined by both its own fundamental productivity and the network productivity of its supplier firms. Customer firms can improve their network efficiencies by sourcing intermediate inputs from efficient upstream firms in the network, which offer intermediates at lower prices.

The formation of production relationships between firms is carried out with the goal of maximizing profits. We assume that only supplier firms can initiate linkages and they face a random relationship cost ζ.[21] This relationship cost is given by $\zeta = \psi\xi$, where ψ represents the mean relationship cost, which is the same for all supplier firms, and ξ is the random component of the relationship cost that varies across firms. We assume that ξ is independently and identically distributed across firms with a cumulative distribution function F_ξ. Additionally, we assume that the random relationship cost shock, ξ, has a mean value of one.

We express the profits of a supplier firm χ attainable from the establishment of a relationship with a particular customer firm χ':

$$\Pi\left(\chi', \chi\right) = \mu^{-\sigma}\left(\mu - 1\right)\Delta_H \Delta(\chi')\Phi(\chi). \tag{17}$$

The profit of the supplier firm χ is a function of the size of the customer firm χ', $\Delta(\chi')$, and its own network productivity, $\Phi(\chi)$. As we have assumed that the upstream supplier firm decides whether to initiate the relationship with a potential customer under an idiosyncratic random relationship cost, we establish the following condition indicating that the upstream firm χ forms a production network with the customer firm χ' when the net profits from doing so are positive:

$$\Pi(\chi', \chi) - \psi\xi > 0. \tag{18}$$

Thus, by incorporating equation (17), the probability that firm χ initiates the production relationship with firm χ' can be specified as

$$m\left(\chi', \chi\right) = F_\xi\left[\frac{\Delta_H \Delta(\chi')\Phi(\chi)}{\bar{\psi}}\right], \tag{19}$$

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[21] This assumption is also made in Lim (2017).

where $\bar{\psi} = \psi\mu^{\sigma}(\mu - 1)^{-1}$. This shows that firms with cost-efficient upstream suppliers have a greater chance to establish downstream trading relationships. It also indicates that firms connected with larger downstream firms are more likely to establish their own supply networks with upstream producers.

3.2.2 Optimal Input and Output Decision

The definitions of network characteristics allow us to express the firm's optimal use of the dirty input, $z(\chi)$, and the bilaterally defined intermediate input, $x(\chi, \chi')$, as well as its total scale of production, $X(\chi)$, in relation to the firm's ability to form supplier and customer relationships:

$$z(\chi) = \Delta_H \Delta(\chi) \kappa(\chi)^{-\sigma} \phi^{\sigma-1}, \tag{20}$$

$$x(\chi, \chi') = \mu^{-\sigma} \Delta_H \Delta(\chi) \Phi(\chi')^{\frac{\sigma}{\sigma-1}}, \tag{21}$$

$$X(\chi) = \Delta_H \Delta(\chi) \Phi(\chi)^{\frac{\sigma}{\sigma-1}}. \tag{22}$$

The use of the dirty input by a firm as depicted in equation (20) depends on three factors: the scale of production determined by household demand and the network demands of customer firms (Δ_H and $\Delta(\chi)$, respectively), the effective price of the dirty input faced by the firm ($\kappa(\chi)$), and the firm's fundamental productivity in using dirty inputs (ϕ).

As with the firm's demand for the dirty input, demand for intermediate inputs and total output described in equations (21) and (22), respectively, are influenced by household demands and the network demands of customer firms. However, the utilization of intermediate inputs is particularly affected by the network efficiency of the supplier firm, $\Phi(\chi')$. When the supplier firm offers intermediates at lower prices, the customer firm demands a larger quantity of intermediates. Similarly, a firm's total output is determined by its own network efficiency, $\Phi(\chi)$, as lower factor prices enable the firm to increase its production.[22]

3.3 Optimal Abatement Investment and Firms' Environmental Accounts

We next study how firm linkages influence firms' optimal investment in pollution abatement and the ensuing impact on firms' environmental accounts. We can simplify the expression for the unit

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[22] From the market clearing condition and the optimal demand for dirty inputs, equations (11) and (20), we can express the household demand shifter as $\Delta_H = Z/[\int_{S_\chi} \Delta(\chi)\kappa(\chi)^{-\sigma}\phi^{\sigma-1} dG_\chi(\chi)]$. From equations (3), (10), and (14), the consumer price index is thus given by $P_H = \mu[\int_{S_\chi} \Phi(\chi)\delta^{\sigma-1} dG_\chi(\chi)]^{1/(1-\sigma)}$.

cost of the dirty input as

$$\kappa(\chi) = \omega + \frac{t\epsilon}{\mathcal{A}(\chi)}, \tag{23}$$

which depicts that larger abatement investments reduce the effective price of the dirty input as emission tax payments are decreasing in abatement efforts.

Firms choose the optimal level of abatement investment to maximize profits. The profit maximization problem yields the following implicit function which determines the optimal $\mathcal{A}(\chi)$:

$$\Psi(\chi) \equiv t\epsilon(\sigma-1)\phi^{\sigma-1}\left(\omega\mathcal{A}(\chi)+t\epsilon\right)^{-\sigma}\mathcal{A}(\chi)^{\sigma-2}(\mu-1)\Delta_H\Delta(\chi)-1=0. \tag{24}$$

Given the optimal demand for dirty inputs and the optimal abatement investments, we are able to derive the equilibrium level of emissions generated by firm χ:

$$e^*(\chi) = \epsilon\phi^{\sigma-1}\Delta_H\Delta(\chi)\mathcal{A}(\chi)^{-1}\kappa(\chi)^{-\sigma}. \tag{25}$$

As emission intensity conventionally refers to the emissions generated per unit of output, firm-level emission intensity, $\Xi(\chi)$, can be calculated as:

$$\Xi(\chi) \equiv \frac{e(\chi)}{X(\chi)} = \epsilon\phi^{\sigma-1}\Phi(\chi)^{-\frac{\sigma}{\sigma-1}}\mathcal{A}\left(\chi\right)^{-1}\kappa\left(\chi\right)^{-\sigma}. \tag{26}$$

Equation (26) reveals that emission intensity increases in the pollution content of dirty inputs (ϵ), as more pollution is generated per unit of input. Additionally, higher efficiency in utilizing dirty inputs (ϕ) raises emission intensities as firms that are more efficient in the use of these inputs will tend to use them more intensively. However, greater network productivity ($\Phi(\chi)$) reduces emission intensities by enabling firms to outsource intermediate inputs at lower prices, reducing the use of dirty inputs.

Abatement investments have varied effects. They have the direct effect of reducing total emissions and improving emission intensity. However, they also lower the effective price of dirty inputs by reducing firms' per-unit emissions tax payment, which has the indirect effect of increasing the firm's dirty input utilization. Thus, the latter effect may attenuate the direct impact of abatement on reducing emissions.

3.4 Firm Sorting, Export Status, and Economic Geography

We have established how firms' environmental accounts are determined by firm linkages that in turn affect optimal abatement investments and input sourcing decisions. Now, we turn our attention to the impact of globalization (i.e., reductions in international trade costs) on the spatial distribution of firms across regions. We specifically examine the types of firms that locate in each region and how this process contributes to disparities in the patterns of total emissions and emission intensities across region types in light of the evidence presented earlier in Section 2.

Our analysis focuses on three main considerations: firm sorting via entry and exit, the determination of firms' export statuses, and the spatial distribution of firms in relation to international trade costs. By studying these factors, we will characterize the mechanisms through which globalization influences the distribution of emissions and emission intensities across regions.

To analyze how market access shapes the spatial distribution of firms and emissions, we consider two regions: core (C) and periphery (P). In the home country H, the set of firms in the core is denoted by S_{χ}^{HC}, while the set of firms in the periphery is denoted by S_{χ}^{HP}. Firms face trade costs to ship goods between regions and countries measured in iceberg terms, meaning that more than one unit of a good must be shipped for one unit to arrive in the destination region, with domestic trade costs faced by firm χ in shipping goods from domestic region i to domestic region j given by $\tau^{ij}(\chi)$. We assume that trade within regions is costless: $\tau^{PP}(\chi) = \tau^{CC}(\chi) = 1$, where τ^{CC} and τ^{PP} denote within-core and within-periphery trade costs, respectively. Trade between regions is costly and these costs are assumed to be symmetric: $\tau^{PC}(\chi) = \tau^{CP}(\chi) = \tau_D(\chi) > 1$, where $\tau_D(\chi)$ denotes domestic inter-regional trade costs. Firms face iceberg international trade costs (on top of inter-regional trade costs in shipping goods to/from ports of entry/exit) of $\tau_B(\chi) > 1$ to export their products to the foreign market, where $\tau_B(\chi)$ denotes international trade costs.

We also introduce a foreign country F, which also consists of a core and periphery region. The set of firms in the core and periphery of F are denoted as S_{χ}^{FC} and S_{χ}^{FP}, respectively, and firms in F face trade costs analogous to those faced by firms in H. We assume that the foreign country is identical to the home country allowing us to focus on firms' location and exporting choices in the home country.

We assume that a firm must pay a fixed cost to enter into the market. Once the firm has decided to enter, it must pay a random fixed cost to locate in either region. We assume the fixed cost of locating in the core region is greater than in the periphery. To simplify the model we normalize the cost of locating in the periphery to be zero. Conditional on the firm's entry, the firm then makes a location choice and decides whether or not to become an international firm. International trade takes place through ports, which are assumed to be located in the core region in both countries. This implies that the (iceberg) trade costs incurred in transactions between home and foreign periphery firms are multiplicative and given by $\tau_{BDD} \equiv \tau_B(\chi) \times \tau_D^2(\chi)$, those between home periphery (home core) and foreign core (foreign periphery) firms by $\tau_{BD} \equiv \tau_B(\chi) \times \tau_D(\chi)$, and those between home and foreign core firms by $\tau_B(\chi)$.

3.4.1 Firm Entry and Exit

Under this environment, we consider the entry and exit problem of firms. The profit of a firm χ that remains in the market can be calculated by subtracting total relationship and entry costs from variable profits, $\pi^{\text{enter}}(\chi; \tau_D(\chi), \tau_B(\chi))$:

$$\Pi^{\text{enter}}(\chi; \tau_D(\chi), \tau_B(\chi)) = \pi(\chi; \tau_D(\chi), \tau_B(\chi)) - \psi_1 M_C^H(\chi; \tau_D(\chi)) - \psi_2 M_C^F(\chi; \tau_D(\chi), \tau_B(\chi)) - \mathbb{C}, \tag{27}$$

where $M_C^H(\chi)$ and $M_C^F(\chi)$ respectively refer to the total mass of customer firms of firm χ across H and F, which are determined by the following general rule $M_C(\chi) = \int_{S_{\chi'} \in H,F} m(\chi', \chi) dG_\chi(\chi')$. Average relationship costs that home country firm χ faces by matching with firms at home and abroad are denoted by ψ_1 and ψ_2, respectively.[23] Thus, $\psi_1 M_C^H(\chi)$ and $\psi_2 M_C^F(\chi)$ represent the total relationship costs borne by firm χ. In our context, relationship costs directly influence firm sorting based on firms' fundamental characteristics as described earlier. The last term, $\mathbb{C}$, in equation (27) is the fixed market entry cost. Based on this setup, the fundamental characteristics, $\chi = (\phi, \delta)$, of the firms that stay in the market in equilibrium under various trade cost regimes are determined by the following zero-profit condition:

$$\Pi^{\text{enter}}(\chi; \tau_D(\chi), \tau_B(\chi)) = 0. \tag{28}$$

3.4.2 Export Status of Firms

Firms that choose to remain in the market must determine their location and export/import statuses. The probability that firm χ will establish a network with foreign trade partner χ' is positively related

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[23] The mean relationship costs between firms across countries are assumed to be greater than those between firms within a country (i.e., $\psi_2 > \psi_1$). This is because, in general, it is more costly for home firms to search for the best trade partners and finally establish relationships with foreign firms; for instance, because of geographical distance, differences in regulatory environments, or information frictions between countries.

to firm χ's expected profits of matching with the foreign firm. This implies that greater network efficiency (demand) of firm χ and larger network demand (efficiency) of the foreign customer raise the likelihood of matching:

$$m_C^F(\chi', \chi; \tau_B(\chi), \tau_D(\chi)) = F_\xi\left[\frac{\Delta_H \Delta(\chi')\Phi(\chi)}{\bar{\psi}_2}; \tau_B(\chi), \tau_D(\chi)\right], \tag{29}$$

$$m_S^F(\chi, \chi'; \tau_B(\chi), \tau_D(\chi)) = F_\xi\left[\frac{\Delta_H \Delta(\chi)\Phi(\chi')}{\bar{\psi}_2}; \tau_B(\chi), \tau_D(\chi)\right], \tag{30}$$

where $\bar{\psi}_2 = \psi_2 \mu^\sigma (\mu - 1)^{-1} \alpha^{1-\sigma}$, $\chi \in (S_\chi^{HP} \cup S_\chi^{HC})$, and $\chi' \in (S_\chi^{FP} \cup S_\chi^{FC})$.[24]

The bilateral matching probabilities that firm χ is matched with a foreign customer and supplier firm χ' are denoted as $m_C^F(\chi', \chi)$ and $m_S^F(\chi, \chi')$, respectively. From this, we can therefore illustrate the total mass of foreign customers and suppliers as the weighted average of the matching probabilities:

$$M_C^F(\chi; \tau_D(\chi), \tau_B(\chi)) = \int_{S_\chi^{FP} \cup S_\chi^{FC}} m_C^F(\chi', \chi; \tau_B(\chi), \tau_D(\chi)) dG_\chi(\chi'), \tag{31}$$

$$M_S^F(\chi; \tau_D(\chi), \tau_B(\chi)) = \int_{S_\chi^{FP} \cup S_\chi^{FC}} m_S^F(\chi, \chi'; \tau_B(\chi), \tau_D(\chi)) dG_\chi(\chi'). \tag{32}$$

We define the "openness" of firm χ, $i(\chi; \tau_D(\chi), \tau_B(\chi))$, based on its total number of foreign trade partners relative to that of the most productive and largest firm in the economy. In doing so, we are normalizing the probability that the largest firm is an international firm to unity:[25]

$$i(\chi; \tau_D(\chi), \tau_B(\chi)) \equiv \frac{M^F(\chi; \tau_D(\chi), \tau_B(\chi))}{\max \ M^F(\chi'; \tau_D(\chi'), \tau_B(\chi'))} \quad \text{for all} \ \ \chi' \in S_\chi, \tag{33}$$

where $M^F(\chi; \tau_D(\chi), \tau_B(\chi)) = M_C^F(\chi; \tau_D(\chi), \tau_B(\chi)) + M_S^F(\chi; \tau_D(\chi), \tau_B(\chi))$. Thus, using the complementary probability, the likelihood of firms operating solely in the domestic market is

$$\hat{i}(\chi; \tau_D(\chi), \tau_B(\chi)) = 1 - i(\chi; \tau_D(\chi), \tau_B(\chi)). \tag{34}$$

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[24] On top of international trade costs, we can additionally introduce foreign market entry costs, the inclusion of which in each firm's problem would decrease the likelihood of foreign matching and increase the mass of exiting firms. Introducing this element, however, would leave our principal findings unchanged.

[25] We can normalize the probability of internationalization by dividing each firm's total (weighted average) number of foreign trade partners by the aggregate number of foreign partners with which all firms in the economy are matched. This approach yields qualitatively similar results.

3.4.3 Spatial Sorting of Firms

Next, we shift focus to explore the location decision of firms. Under the assumption that locating in the core region is more costly for firms than locating in the periphery region, the extent of this cost difference is governed by two parameters: a mean value common to all firms, φ, and by a random shock with mean one, ρ, which is drawn from a cumulative density function H_ρ.[26] Note that, conditional on entering the market, a firm can choose to locate in the core and pay $\mathbb{C} + \varphi\rho$, or it can locate in the periphery and pay only $\mathbb{C}$ in total entry costs.[27] A firm will decide to locate in the core if the expected net profit obtainable in the core exceeds that in the periphery:

$$\Pi^{HC}(\chi; \tau_D(\chi), \tau_B(\chi)) - \varphi\rho > \Pi^{HP}(\chi; \tau_D(\chi), \tau_B(\chi)), \tag{35}$$

where $\Pi^{HC}(\chi)$ is the expected profit of firm χ when locating in the core region and $\Pi^{HP}(\chi)$ is the expected profit when locating in the periphery.

The probability of locating in the core, $r(\chi; \tau_D(\chi), \tau_B(\chi))$, can thus be expressed as

$$r(\chi; \tau_D(\chi), \tau_B(\chi)) = H_\rho \left[\frac{\Pi^{\text{net}}(\chi; \tau_B(\chi), \tau_D(\chi))}{\varphi} \right], \tag{36}$$

where $\Pi^{\text{net}} = \Pi^{HC}(\chi; \tau_D(\chi), \tau_B(\chi)) - \Pi^{HP}(\chi; \tau_D(\chi), \tau_B(\chi))$. Therefore, the likelihood of a firm locating in the periphery region, $\hat{r}(\chi; \tau_D(\chi), \tau_B(\chi))$, is the complementary probability of locating in the core:

$$\hat{r}(\chi; \tau_D(\chi), \tau_B(\chi)) = 1 - r(\chi; \tau_D(\chi), \tau_B(\chi)). \tag{37}$$

3.4.4 Classification of Firms by Types

Based on the results derived thus far we are able to identify the total mass of firms of each type according to their locations and export statuses as the product of the probabilities of entry/exit,

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[26] This assumption is similar to that introduced in the previous section in which firms face an idiosyncratic relationship cost shock from a random probability distribution.

[27] Recall we normalize the periphery-specific location cost to be zero.

location, and matching with foreign firms. :

$$M^{CD} = \int_{S_\chi} \underbrace{p\left(\Pi^{\text{enter}}(\chi) > 0\right)}_{\text{Prob. of entry}} \times \underbrace{\hat{\imath}(\chi; \tau_D(\chi), \tau_B(\chi))}_{\text{Prob. to be a domestic firm}} \times \underbrace{r(\chi; \tau_D(\chi), \tau_B(\chi))}_{\text{Prob. to be a core firm}} dG_\chi(\chi), \tag{38}$$

$$M^{PD} = \int_{S_\chi} \underbrace{p\left(\Pi^{\text{enter}}(\chi) > 0\right)}_{\text{Prob. of entry}} \times \underbrace{\hat{\imath}(\chi; \tau_D(\chi), \tau_B(\chi))}_{\text{Prob. to be a domestic firm}} \times \underbrace{\hat{r}(\chi; \tau_D(\chi), \tau_B(\chi))}_{\text{Prob. to be a periphery firm}} dG_\chi(\chi), \tag{39}$$

$$M^{CI} = \int_{S_\chi} \underbrace{p\left(\Pi^{\text{enter}}(\chi) > 0\right)}_{\text{Prob. of entry}} \times \underbrace{i(\chi; \tau_D(\chi), \tau_B(\chi))}_{\text{Prob. to be an international firm}} \times \underbrace{r(\chi; \tau_D(\chi), \tau_B(\chi))}_{\text{Prob. to be a core firm}} dG_\chi(\chi), \tag{40}$$

$$M^{PI} = \int_{S_\chi} \underbrace{p\left(\Pi^{\text{enter}}(\chi) > 0\right)}_{\text{Prob. of entry}} \times \underbrace{i(\chi; \tau_D(\chi), \tau_B(\chi))}_{\text{Prob. to be an international firm}} \times \underbrace{\hat{r}(\chi; \tau_D(\chi), \tau_B(\chi))}_{\text{Prob. to be a periphery firm}} dG_\chi(\chi)w \tag{41}$$

where the superscripts in equations (38)–(41) refer to domestic and international firms in the core region, (CD) and (CI), and in the periphery, (PD) and (PI). In contrast with the continuously valued probability of spatial sorting and foreign matching, the probability of entry/exit is binary, i.e., either zero or one.

3.5 Visual Conceptualization of Firm Types

Based on the theoretical setup described thus far, we provide a conceptualization of firm types on a (ϕ, δ)-grid as a function of their entry/exit statuses, locations, and export/import statuses. Figure 4 conceptually illustrates the distribution of firm types in relation to their fundamental characteristics under high versus low international trade costs.[28] Panel (a) of Figure 4 illustrates that large and efficient firms (high δ and ϕ) are likely to be international firms (reflected by the mass of firms in the orange colored area) as these are the firms that find it most profitable to establish production relationships with foreign counterparts. The least productive and smallest firms exit (the firms in the gray colored area) because they are not able to afford the fixed cost of entry and relationship costs required for staying in the market. As we assume that the fixed cost of entering the periphery is lower than the core, firms may find it more profitable to locate in the periphery and pay the shipping cost to the port (located in the core) when domestic/international trade costs are fairly low.

As international trade costs decrease, a scenario depicted in panel (b) of Figure 4, more firms are incentivized to locate in the core region (marked by the green and red colored areas). The largest of these firms establish networks directly with foreign firms, while the smaller of these firms locate in

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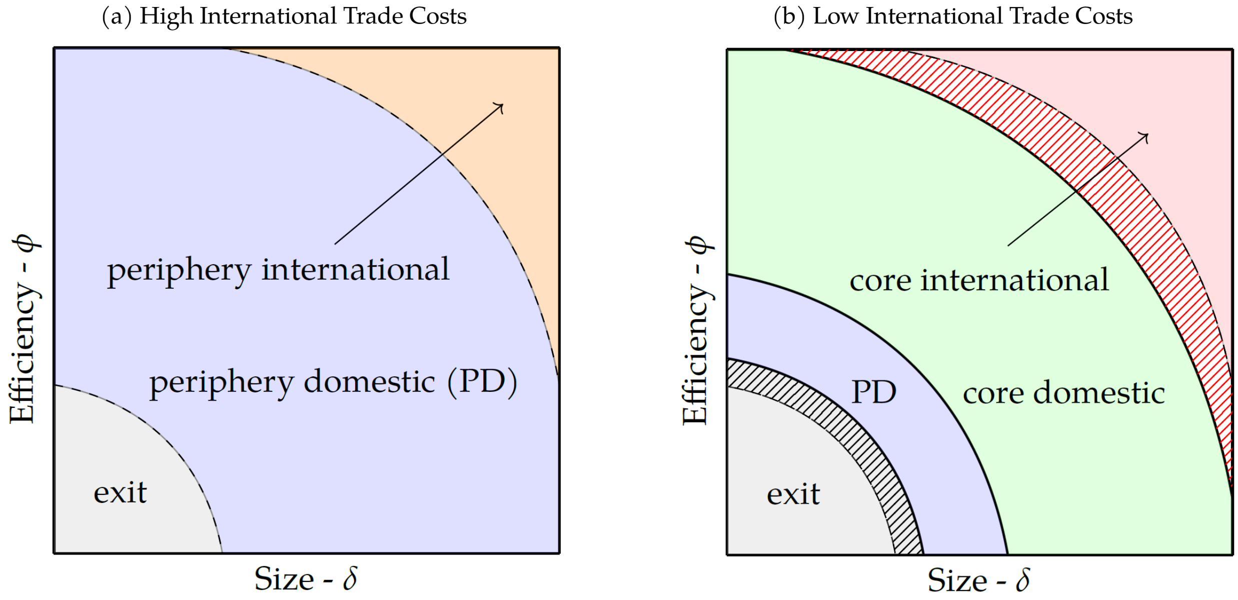
[28] Note that "high" versus "low" here do not correspond to specific numeric values of international trade costs. We conduct numerical simulations in the following section to directly quantify these relationships.

Figure 4: Firm Type Conceptualization


(a) High International Trade Costs

(b) Low International Trade Costs

Notes: Figures present a conceptual illustration of firm types by export statuses and location depending on the level of international trade frictions under high versus low international trade costs (panel (a) and panel (b), respectively). The vertical and horizontal axes respectively indicate firms' idiosyncratic efficiencies and consumer demands (size). Hatch-shaded areas in panel (b) correspond to the firms from panel (a) that exit (black hatch mark area) or become international firms (red hatch mark area) in moving to the low trade cost scenario.

the core region to be in close proximity to the large international firms. As a result, only relatively less productive and smaller firms will choose to locate in the periphery region (i.e., the firms in the blue shaded area) and are likely to serve only the domestic market. The cutoffs distinguishing firm types would vary due to the resulting changes in (expected) profits and costs. The export cutoffs would shift in toward the origin as there are positive feedback effects that enable firms to form more relational supply chains with the best foreign trade partners. This feedback effect, or positive network externality, thereby allows more firms to profitably locate in the core region and to become internationals (the firms in the red hatch mark area). The exit threshold could move in either direction in response to changes in trade costs. Trade cost reductions intensify competition causing more firms to exit. However, the positive network externalities also strengthen due to reductions in trade barriers and generate efficiency gains for the smallest (and/or least productive) firms. If the former effect dominates the latter we would expect the exit threshold to shift outwards from the origin (the mass of firms in the black hatch mark area); however, it would otherwise shift in and allow more firms to survive in response to trade cost reductions.

3.6 Regional Environmental Accounts

We have established how networks affect the level of abatement investments, the total emissions and emission intensities of firms, and how firms' locations and export statuses are determined in a setting with endogenous firm linkages. Hence, we are able to characterize the role of firm networks in determining regional environmental quality in terms of total emissions and emission intensities.

The total pollution emitted in core and periphery regions (E^C and E^P, respectively) can be expressed as weighted averages of emissions by core and periphery firms, calculated as:

$$E^C = \int_{S_\chi} \underbrace{p\left(\Pi^{\text{enter}}(\chi) > 0\right) \times r(\chi) \times e(\chi)}_{\text{Total emissions by a core firm}} dG_\chi(\chi) \tag{42}$$

$$E^P = \int_{S_\chi} \underbrace{p\left(\Pi^{\text{enter}}(\chi) > 0\right) \times \hat{r}(\chi) \times e(\chi)}_{\text{Total emissions by a periphery firm}} dG_\chi(\chi). \tag{43}$$

Likewise, the regional emission intensities of both regions (EI^C and EI^P) can be derived as the ratio of total emissions to the level of production:

$$EI^C = \frac{\int_{S_\chi} p\left(\Pi^{\text{enter}}(\chi) > 0\right) \times r(\chi) \times e(\chi) dG_\chi(\chi)}{\int_{S_\chi} \underbrace{p\left(\Pi^{\text{enter}}(\chi) > 0\right) \times r(\chi) \times X(\chi)}_{\text{Total output by a core firm}} dG_\chi(\chi)}, \tag{44}$$

$$EI^P = \frac{\int_{S_\chi} p\left(\Pi^{\text{enter}}(\chi) > 0\right) \times \hat{r}(\chi) \times e(\chi) dG_\chi(\chi)}{\int_{S_\chi} \underbrace{p\left(\Pi^{\text{enter}}(\chi) > 0\right) \times \hat{r}(\chi) \times X(\chi)}_{\text{Total output by a periphery firm}} dG_\chi(\chi)}. \tag{45}$$

The theoretical results that we have established allow us to analyze the interplay of international trade cost reductions and firm linkages in shaping regional environmental quality as mediated by endogenously established firm networks.

4 Numerical Exercise

We next undertake a series of numerical exercises to further investigate the analytical relationships derived thus far. To do this, we calibrate the model's fundamental parameters to real-world data and frame our analysis to consider the generation of a local pollutant (nitrogen oxide, or NO_x) by firms in a two-region economy with active environmental regulations. After describing our calibration procedure, we provide simulation evidence on the roles of endogenous production networks and international trade costs in shaping the distribution of firms across regions. We then characterize the implications of this for regional environmental accounts, and specifically assess the importance of the endogenous networks assumption over alternative modeling assumptions on firm-to-firm relationships.

4.1 Parametric Assumptions

To operationalize the theoretical model, we begin by assuming that the fundamental productivity (ϕ) and size (δ) of a firm are strictly positive random variables (i.e., $(\phi, \delta) \in \mathbb{R}_{++}$) whose logged values are assumed to be drawn from independently and identically distributed standard normal distributions.[29] We additionally assume that the distribution of the relationship cost shock, F_ξ, follows a Weibull distribution since this distribution yields an economic interpretation as the minimum cost among a series of cost draws within a given relationship.[30]

We characterize the location decision of firms by introducing a random location cost shock. We normalize each firm's cost of locating in the periphery to zero and assume that the difference in the core and periphery location costs follows a random process H_ρ. We assume that H_ρ also follows a Weibull distribution. This implies that the location cost of a firm drawn from H_ρ is the minimum location cost among a series of cost draws.

4.2 Parameter Values

The solution of the theoretical model is characterized by a set of 11 fundamental parameters. These parameters and the sources for their calibrated values are described in Table 1.

The values for the mean domestic relationship cost (ψ_1), the shape parameter for the relationship cost distribution (s_ξ), the elasticity of substitution (σ), and domestic trade costs (τ_D) are obtained directly from Lim (2017), who calibrates these parameters based on business data from Capital IQ and Compustat.[31] The mean foreign relationship cost (ψ_2) is proxied by estimates on information frictions (matching efficiency) between Japanese firms as measured in Sato (2009). The average difference in location costs across regions (φ) is chosen such that the share of core firms in the model mirrors that of the real-world United States, which is around 57% based on data from the US Census Bureau's Statistics of US Businesses (2017). Additionally, we have determined the entry cost in our model in a manner that ensures a fraction of firms exit, but never exceeding 20%. This

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[29] This implies that negative realizations of $\log(\phi)$ and $\log(\delta)$ correspond to values of ϕ and δ falling in the (0,1) interval and positive realizations of $\log(\phi)$ and $\log(\delta)$ correspond to values of ϕ and δ greater than one.

[30] See Lim (2017) for more detail.

[31] Lim calculates both the overall level of trade costs (0.688) and the elasticity of trade costs with respect to the distance between firms (0.348). He then assumes that the functional form of domestic trade frictions is equal $\tau_D = (1 + 0.688 \times \mathit{distance})^{0.348}$. We obtain the value 1.17 based on his assumption that firms are separated from each other with a maximum distance of one on a unit circle.

Table 1: Parameter Choice

Parameter	**Definition**	**Value**	**Source**
ψ_1	Mean domestic relationship cost	0.216	Lim (2017)
ψ_2	Mean foreign relationship cost	0.6	Sato (2009)
s_ξ	Shape of relationship cost distribution	0.957	Lim (2017)
σ	Elasticity of substitution	4.0	Lim (2017)
τ_D	Domestic trade cost	1.17	Lim (2017)
φ	Mean difference in location cost	0.11	Chosen so as to have the share of core region firms close to 60% under frictionless international trade
D	Supply of dirty input	1.0	Normalized to one
ϵ	Pollution conversion parameter	0.000094	1 MMBtu of heat from burning natural gas creates 0.000094 metric ton of NO_x
ω	Price of dirty input	1.0	Numeraire
t	Tax rate	0.134	Authors' calculation based on marginal damage estimates of NO_x (dollar per ton) reported in Holland et al. (2016)
$\mathbb{C}$	Entry cost	0.001	Chosen to have $<$ 20% of firms exit

Notes: Table gives the calibrated parameter values used in the numerical analyses. We use data from US Census Bureau (2017), the Manufacturing Energy Consumption Survey (MECS) by the Energy Information Administration (EIA), the National Emission Inventory (NEI) by the Environmental Protection Agency (EPA), and estimates of marginal damages from NO_x in the United States from Holland et al. (2016) to obtain the average relocation costs, emission tax rate, and pollution conversion parameters. The rest of the parameters are obtained from the indicated sources.

choice aligns with figures given by Hopenhayn (1992), who describes an annualized attrition rate of 10% for US manufacturing firms.

On top of the parameter values used to define the characteristics of firm-to-firm production networks, we also obtain information to calibrate the model variables relating to use of the dirty input and emissions. We normalize the total supply of the dirty input (D) to one. Among the various energy sources used by firms, we particularly focus on heat inputs from natural gas (versus coal, petroleum, or some other carbon-intensive energy source) to play the role of the dirty input in our calibration, as nitrogen oxides (NO_x) are one of the main pollutants (along with CO_2 and other local pollutants) generated from the combustion of natural gas. According to the EIA, natural gas has become the primary energy source of the US manufacturing sector, accounting for roughly half of US industrial energy use as of 2016 (Monthly Energy Review, September 2017). Moreover, natural gas tends to be more homogeneous than coal or petroleum.[32]

To determine the pollution conversion and tax rate parameters, we utilize data from four sources: (a) the Manufacturing Energy Consumption Survey (MECS) by the Energy Information Administration (EIA), (b) the Statistics of U.S. Businesses (SUSB) by the Census, (c) the National Emission Inventory

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[32] See the EIA's "Use of Energy Explained" (`www.eia.gov/energyexplained/index.php?page=us_energy_industry`).

(NEI) by the Environmental Protection Agency (EPA), and (d) estimates of marginal damages from NO_x in the United States from Holland et al. (2016).

The MECS database indicate that the total heat input consumption of the U.S. manufacturing sector (NAICS industries 311–339) from natural gas combustion in 2017 was 6,362 trillion British Thermal Units (TBtu). The NEI database shows that the total NOx pollution from natural gas combustion in industrial boilers was 601,988 tons in 2018, the closest available data to 2017. To convert these sectoral measures to the firm level, considering a total of 5,996,900 U.S. firms in 2017 (SUSB), we calculate average per-firm heat input consumption as 1,060.881 million British Thermal Units (MMBtu) (= 6,362 TBtu / 5,996,900 firms) and average per-firm emissions NOx as 0.1 ton (= 601,988/5,996,900). Consequently, the NO_x emission per MMBtu, which we define as the pollution conversion parameter (ϵ), is calculated as 0.000094 ton/MMBtu (= 0.1/1,060.881).

For the pollution tax rate (t), we rely on the average marginal damage estimates of NO_x in the United States from Holland et al. (2016), calculated to be \$4,257.63 per ton (in year 2000 dollars) in 2011. Thus, the marginal damage per MMBtu at the firm level is calculated to be \$0.4/MMBtu (= \$4,257.63 × 0.000094 ton). As the dirty input is assumed to be a numeraire in the model, we normalize the marginal damage estimate to \$0.134/MMbtu (= \$0.4/\$2.99) given that the (Henry Hub spot) price of natural gas in 2017 was \$2.99/MMBtu.

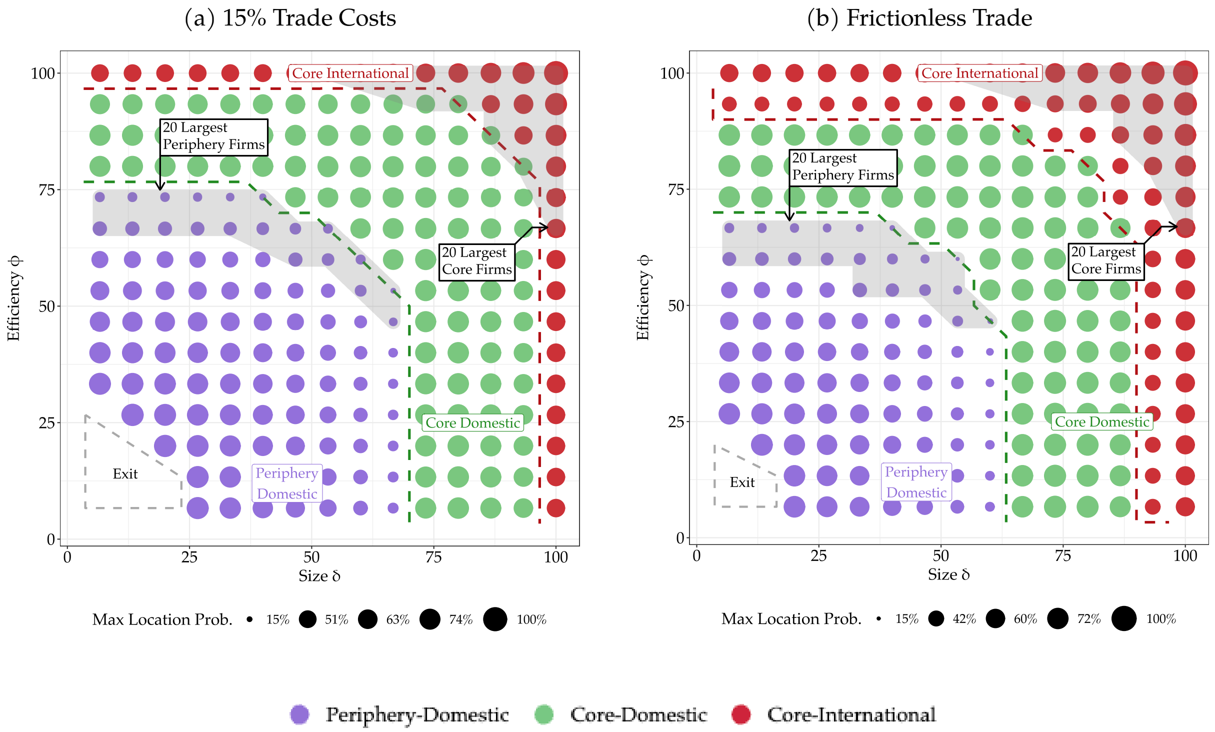
4.3 Firm Locations, Outsourcing, and Environmental Accounts

4.3.1 Trade Cost Reduction and Spatial Sorting of Firms to the Core

We first verify the conceptual illustration presented in Figure 4 through a numerical analysis. We identify firm types by comparing two cases where international trade costs decline from 15% (i.e., $\tau_B = 1.15$) to zero (i.e., $\tau_B = 1$). We then illustrate the distribution of firm types on a 15-by-15 grid over (ϕ, δ) space corresponding to 225 total firm entities based on the maximum probability that a firm either exits or becomes one of the four possible types of firm: periphery-domestic, periphery-international, core-domestic, and core-international. The sizes of the bubbles represent the maximum probability over the four possible firm types that a firm with a given draw of (ϕ, δ) is of a particular type (conditional on the firm not exiting). Vacant spaces represent exiting firms.

In line with the main analytical results established earlier, Figure 5 illustrates that firms which are larger in size and/or more productive are more likely to be located in core regions and engage in international commerce. Under frictionless international trade, only periphery-domestic, core-domestic, and core-international firms exist, which underscores the relationship between

Figure 5: Firm Types by Fundamental Characteristics



Notes: Figure depicts the (maximum) probability that a firm will be of a given type (location and export status) under frictionless international trade for each combination of firm characteristics in the (ϕ, δ) grid space. Larger bubbles indicate a higher probability that a firm with the given characteristics will be the indicated type. Shaded areas correspond to the 20 largest firms (in terms of output) in each region. The x- and y-axes correspond to the quantile of each firm's fundamental size and efficiency draws, respectively.

international trade and the spatial distribution of firms. When comparing the two sub-figures, it becomes more apparent from the inward shift of the export cutoff (the red dashed line) and spatial cutoff (the green dashed line) toward the origin that the reduction of international trade frictions encourages more firms to spatially sort to the core and leads them to be internationals.[33]

The borders differentiating firms' types (indicated by the dashed lines) are concave, reflecting the joint positive influence of efficiency and size on the probability of firms being a specific type. It is important to note that bubble sizes near the cutoffs are smaller (i.e., the probability of being the indicated type is lower), which corresponds to firms in these areas being closer to the margin of firm types either in terms of geography or their status as domestic versus international. For example, the 20 largest firms in the periphery region (marked by the shaded area over the periphery-domestic region) are less likely to be characterized as periphery-domestic compared to firms located near the

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[33] We also witness the counteracting forces arising from intensified competition and positive network externality via changes in the exit cutoff (the gray dashed line).

origin of the grid.

4.3.2 Firms' Environmental Accounts

Having established the geographical distribution and the export/import statuses of firms in relation to firms' productivity and size, we next portray firm-level environmental accounts in relation to these characteristics under frictionless trade as shown in Figure 6. Here, instead of probabilities, bubble sizes correspond to the firm's emissions or emissions intensities. The legend plots the size of the bubbles that correspond to the 25th, 50th, 75th, and 100th percentile of firm-level emissions or emission intensities.[34] An important feature of the figure is the visible contrasting pattern in firms' total emissions, which are shown in panel (a), versus their emission intensities, which are shown in panel (b). Specifically, panel (a) of Figure 6 shows that firms in the core region emit more pollution than firms in the periphery. In contrast, panel (b) of Figure 6 illustrates that core firms exhibit lower emission intensities compared to relatively inefficient and smaller firms in the periphery region. This result accords with the stylized fact describing the real-world geographical distribution of emissions versus emission intensities depicted earlier in Figure 2.

To make a direct comparison between firms in the two regions, we highlight the 20 largest firms (in terms of output) in the core and periphery regions with shaded areas. Apparent from panel (a) of Figure 6 is that the largest core-international firms (those in the shaded region in the upper right) generate significantly more emissions than their counterparts in the periphery as evidenced by the size of the bubbles in the respective shaded regions. This outcome is largely attributable to the scale effect resulting from frictionless international trade: reduced trade costs cause large and productive core firms to use more production factors, including the dirty input, compared to their periphery counterparts. This observation is supported by panel (a) of Figure 7, which depicts the use of the dirty input by firms of different types. The core region not only exhibits a larger number of firms contributing to emissions but also greater individual firm-level use of dirty inputs causing emissions. Despite the greater use of dirty inputs by core firms, panel (b) of Figure 7 shows that core firms are able to undertake more expenditures on abatement compared to periphery firms, which enables them to limit the increase in emissions resulting from enlarged production.

We next explore the factors that explain the lower emission intensities of core firms compared to those in the periphery. We particularly scrutinize two pathways through which firms are able to attenuate the rise in emissions resulting from an increase in output. The first relates to a firm's *abatement*

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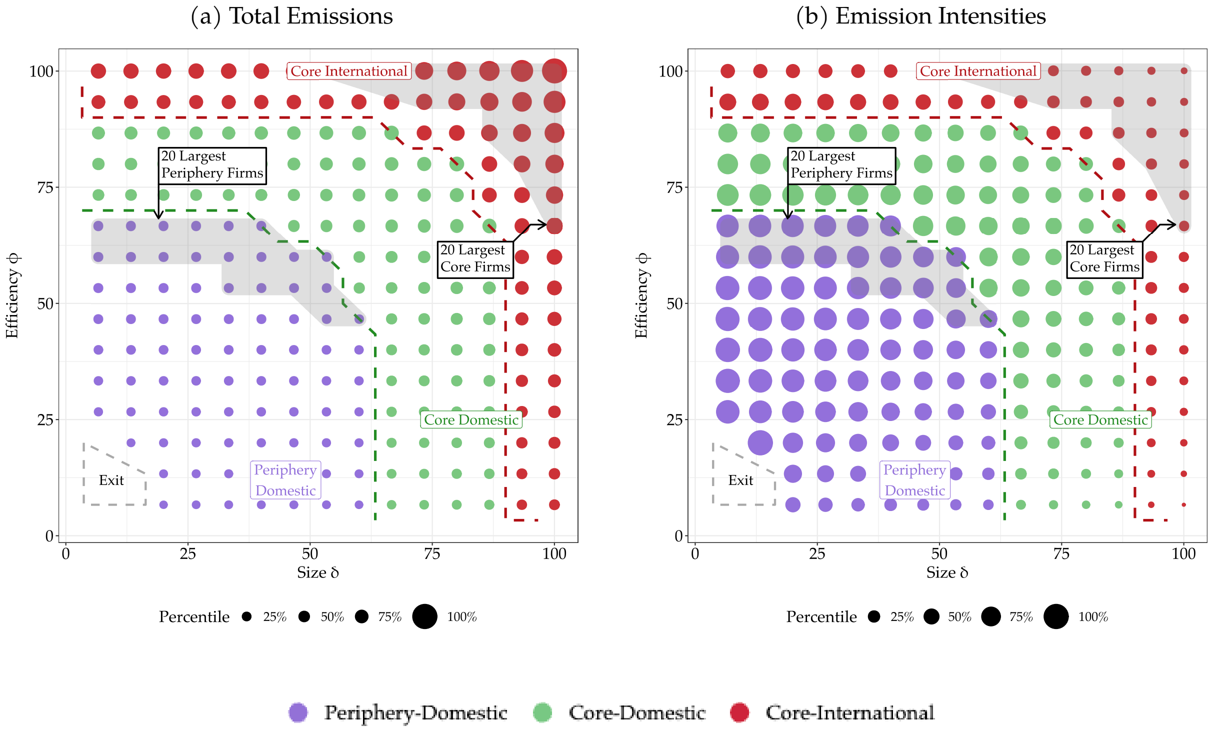
[34] Relative measures represent the differences among firms more clearly than absolute measures, because of normalization of the dirty input and numeraire choice.

Figure 6: Environmental Accounts by Fundamental Characteristics


(a) Total Emissions

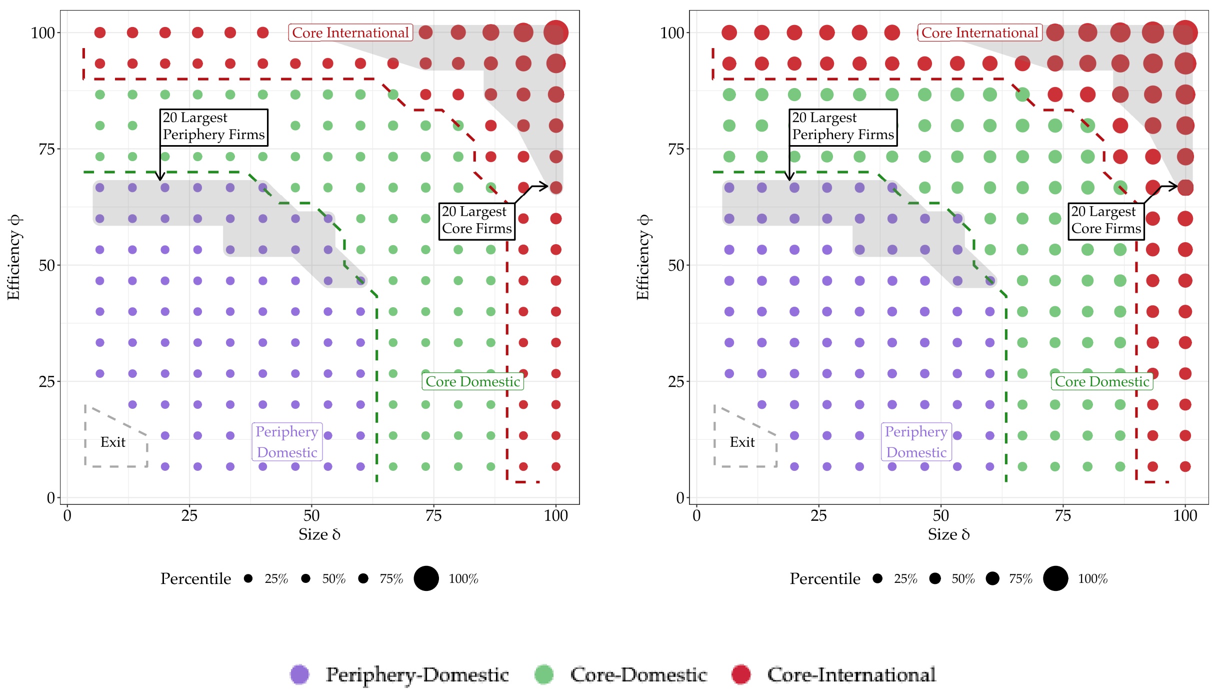
(b) Emission Intensities

Notes: Figure illustrates the total emissions and emission intensities of various firm types under frictionless international trade. Each bubble's size represents a firm's optimal emissions or emission intensities. The legend indicates a firm's result as its percentile in the distribution of optimal firm-level emissions or emission intensities, displaying the 25th, 50th, 75th, and 100th percentile outcomes. Shaded regions indicate the 20 largest firms (in terms of output) in each region. The x- and y-axes correspond to the quantile of each firm's fundamental size and efficiency draws, respectively.

investment intensity, i.e., the ratio of a firm's level of abatement investments to its total variable costs. The second pertains to a firm's *dirty input intensity*. We measure dirty input intensity as the share of a firm's network efficiency that arises from its use of dirty inputs, that is, $(\phi/\kappa(\chi))^{\sigma-1}/\Phi(\chi)$. This measure allows us to measure the importance of dirty input use in production, relative to the firm's ability to outsource. The key principle that derives from these two channels is that a firm's emissions can be reduced either by substituting outsourced intermediates in place of dirty inputs or by investing in abatement measures. Figure 8 visually depicts these two mechanisms.

Panel (a) of Figure 8 shows that, on average, periphery (-domestic) firms, and particularly the smallest and least productive ones, engage most intensively in abatement investments due to their limited capabilities to establish production relationships with other firms. It is also important to note that, as shown in panel (b) of Figure 7, this does not imply that international firms in the core region invest *less* in abatement than domestic firms in the periphery; in fact, core firms invest more in abatement due to their higher profitability, though *less intensively* than those in the

Figure 7: Distribution of Firms by Use of Dirty Input and Abatement Investment Level


(a) Dirty Input Demand

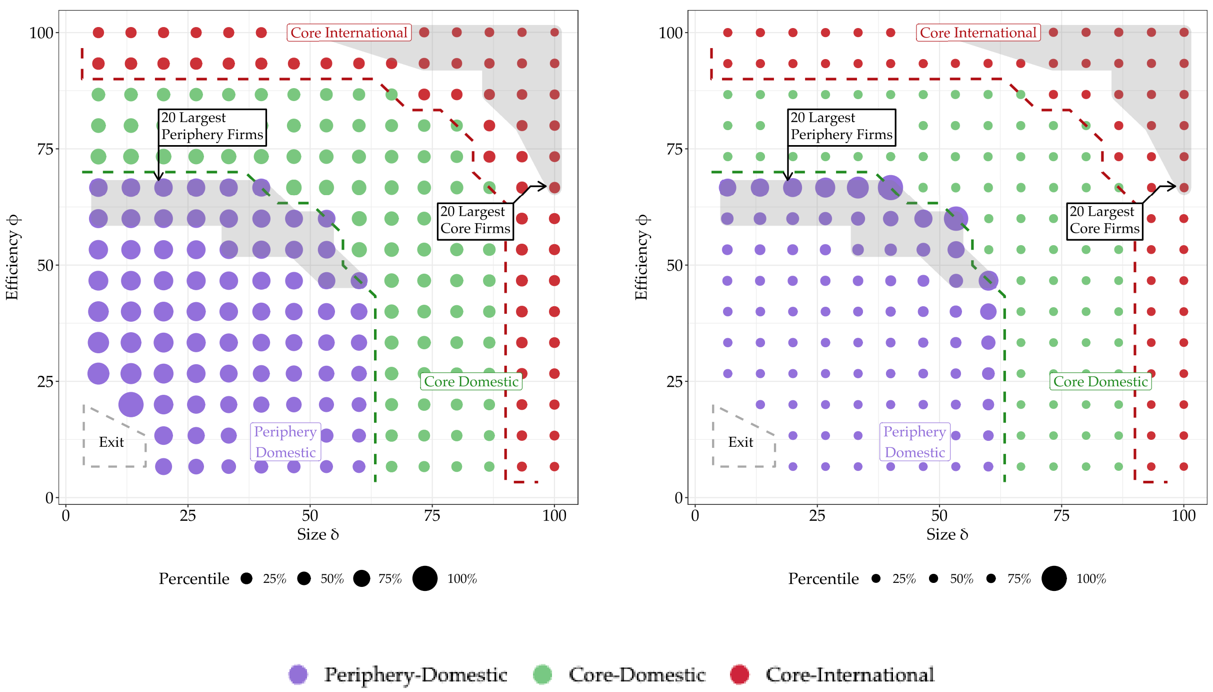
(b) Abatement Investment

Notes: The figure illustrates the total demand for the dirty input and abatement investment for different firm types under conditions of frictionless international trade, represented by varying bubble sizes. The legend indicates a firm's dirty input demand and abatement investment percentile within the distribution of optimal firm-level dirty input demand and abatement investment, displaying the sizes of outcomes at the 25th, 50th, 75th, and 100th percentiles. Shaded areas correspond to the 20 largest firms (in terms of output) in each region. The *x*- and *y*-axes correspond to the quantile of each firm's fundamental size and efficiency draws, respectively.

periphery. However, core firms manage to reduce the share of abatement investment relative to total expenditures on intermediate inputs and abatement measures thanks to their dual approach of enhancing production efficiency through intermediate input sourcing.

This outcome is highlighted in panel (b) of Figure 8, which depicts that core firms tend to use the dirty input less intensively compared to their periphery (domestic) counterparts. The figure additionally emphasizes that the largest periphery firms use the dirty input more intensively than any other firms in the economy. This is attributable to the fact that productive and larger firms (i.e., core-international firms) find it more advantageous to establish production networks, both domestically and internationally, enabling them to source intermediates that can replace dirty inputs. On the other hand, periphery firms that exclusively engage in domestic commerce have limited scope to establish such networks, which leads them to rely more heavily on dirty inputs.

Figure 8: Abatement Investment and Dirty Input Intensities


(a) Abatement Investment Intensity

(b) Dirty Input Intensity

Notes: Figure depicts the abatement investment and dirty input intensities for different firm types under frictionless international trade. Each continuously sized bubble corresponds to a firm's optimal abatement investment or dirty input intensities. The legend expresses a firm's outcome as its percentile in the distribution of optimal firm-level abatement investment or dirty input intensities, showing the size of the 25th, 50th, 75th and 100th percentile outcomes. Shaded areas correspond to the 20 largest firms (in terms of output) in each region. The x- and y-axes correspond to the quantile of each firm's fundamental size and efficiency draws, respectively.

4.4 Globalization, Economic Geography and Regional Environmental Quality

We have studied the role of networks in determining firm-level total emissions and emission intensities. One of the key findings of this analysis was that total emissions are positively related to total production. As core firms tend to produce higher levels of output thanks to more robust networks, core firms become "dirtier" in the aggregate than periphery firms. However, core firms are "cleaner" *per unit of output* than periphery firms, largely due to their outsourcing activities.

To demonstrate how globalization impacts these relationships and to highlight the role endogenous production networks play in explaining these relationships we conduct several experiments. Specifically, we first provide a numerical illustration of the impact of globalization on these relationships as reflected by decreases in international trade costs on the allocation of firms between core and periphery regions. To do this, we examine two scenarios: one with iceberg international trade costs of 15%, and the other with frictionless international trade.[35] Moreover, we explore how emissions and emission intensities at the firm level translate into aggregate regional emissions and intensities, which drives geographical differences in environmental outcomes.

Secondly, to emphasize the role of endogenous production networks in driving these results, we contrast our endogenous production network regime with a scenario where firms are randomly matched with other firms. This counterfactual assumes that buyers and suppliers randomly match with some exogenous probability that does not adjust with trade costs. Henceforth, we refer to this case as random network regime.[36]

The results from the two network regimes are distinct in several ways. Under endogenous networks, firms match with potential trade partners based on expected profitability. This implies that the largest and most productive firms are more likely to establish networks with other firms. The establishment of production networks further improves the profitability of these top firms, while simultaneously improving the network connectivity of their suppliers and customers. These external benefits that spill over from the top firms to their trading partners also accrue to the trading partners' other trade partners. We refer to this phenomenon as the network externality. Importantly, the network externality increases in intensity when international trade costs decline as it directly improves firms' ability to form new supply relationships. Under the random network regime, however, the role of the network externality is significantly weakened since firms are connected in a non-optimal way. Furthermore, when international trade costs decline under this regime the network externality does not change in intensity, since firms cannot form new relationships. This implies that the set of trade partners does not change in response to changes in trade costs, a result that explains the differences between the random and the endogenous network regimes.

4.4.1 Trade Cost Reductions and Economic Geography

Figure 9 displays how the level of international trade costs determines the share of firms located in the core region under the alternative assumptions on network structure. The darker blue bars illustrate the share for the baseline model in which firm networks are endogenously established, while the lighter blue bars describe the share in a setting of random networks.

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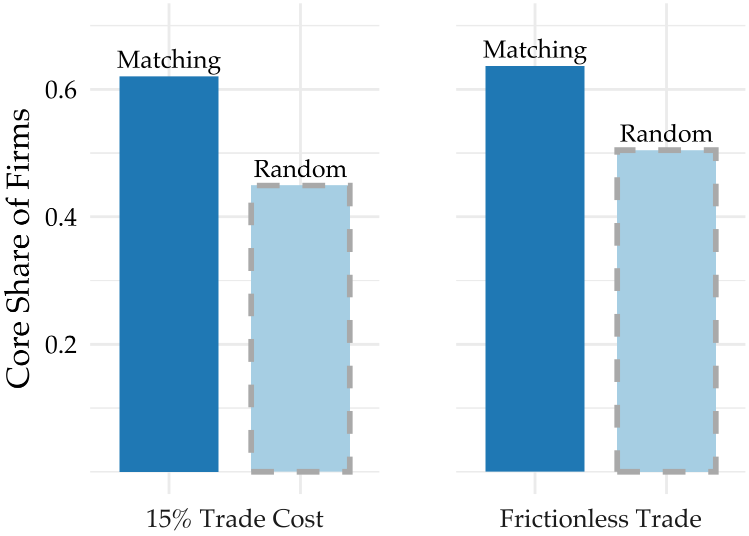
[35] The 15% value that we adopt is effectively arbitrary, though it lies within the empirical range of international trade costs from the literature identified in Anderson and van Wincoop (2004). We note, however, that this value is roughly in the same range as the relative trade costs for US states as calculated based on state-level estimates of multilateral resistance terms as summarized in Anderson and van Wincoop (2004).

[36] In this scenario we randomly assign each firm pair a probability of matching that is drawn from a uniform distribution. The distribution has a lower bound of zero and a mean equal to the average probability of any two firms matching in our endogenous model. That is, the average probability of any two firms matching in the endogenous and random model are

Figure 9: Trade Cost Reductions and the Spatial Sorting of Firms to the Core



Notes: Figure depicts the share of firms located in the core region in the endogenous networks model versus the random probability model under a 15% international trade cost and frictionless international trade, respectively.

The results of both regimes demonstrate that the reduction of international trade costs results in a greater share of firms locating in the core region. This is due to the enhanced opportunities for establishing supply networks with foreign trade partners under lower values of international trade costs. However, it is important to highlight the significant contrast in the degree of firm sorting toward the core region observed in the endogenous network model versus the random network model. Comparing the results from these alternative frameworks, it is apparent that the spatial concentration of firms in the core region is considerably diminished when firms are assumed to form relationships randomly rather than optimally. The reason for this lies in the fact that optimal network formation not only prompts large and productive firms to concentrate in the core regions, but also encourages smaller, less efficient firms to locate alongside larger firms due to the improvements in expected profitability and matching probability. This outcome can be interpreted as a positive network spillover effect. In comparison, the random network model neglects these network spillover effects and only captures the impact of trade cost reductions, which results in diminished incentives for firms to locate in the core region relative to the endogenous network setting.

4.4.2 Economic Geography and Regional Environmental Quality

Lastly, we investigate the impact of globalization on regional environmental disparities as shaped by the dynamics of economic geography. Figure 10 portrays the differences in environmental accounts

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set to be equal.

between the core and periphery regions under alternative levels of international trade costs. Notably, panel (a) shows that the total emission in the core region increases while that in the periphery region declines in response to the reduction in international trade costs. This result is primarily attributable to the fact that the decrease in trade costs results in more firms locating in the core region, a pattern already observed in Figure 9. The reduction in trade costs also fosters an expansion in the scale of production for the firms located in the core. While the random network regime captures the pattern of pollution concentrating in the core region as trade costs decrease similar to the endogenous network regime, it clearly does not capture the pattern of higher emissions in the core region under the costly trade scenario. This pattern accords with the earlier result that the random network regime does not fully capture the forces that drive the concentration of firms and economic activity in the core region.

Panel (b) of Figure 10 portrays the divergent patterns of emission intensities between the core and periphery regions in line with the initial observations discussed in Section 2. The graph reveals that a reduction in international trade costs contributes to improved emission intensities for both core and periphery regions. This phenomenon is rooted in the spatial sorting of firms toward the core, enabling easier access to foreign intermediate inputs, causing the positive environmental spillover effect toward the periphery.

More specifically, as the core region becomes a hub for firms, they can significantly expand their outsourcing activities to more efficient firms in the foreign country.[37] This strategic outsourcing helps firms curtail the growth of total emissions that would otherwise arise from the larger scale of production if they had to rely exclusively on supply relationships with domestic firms.[38] Conversely, in the periphery region, firms prioritize abatement investments over outsourcing due to the limited presence of large and efficient supplier firms in this region. Consequently, periphery firms tend to use the dirty inputs more intensively, leading to elevated emission intensity compared to the core regions.

Globalization notably improves the emission intensity of the periphery region. This occurs because reductions in barriers to international trade enhance the profitability of core firms, prompting them to establish supply chains with periphery firms in what can be described as negative assortative

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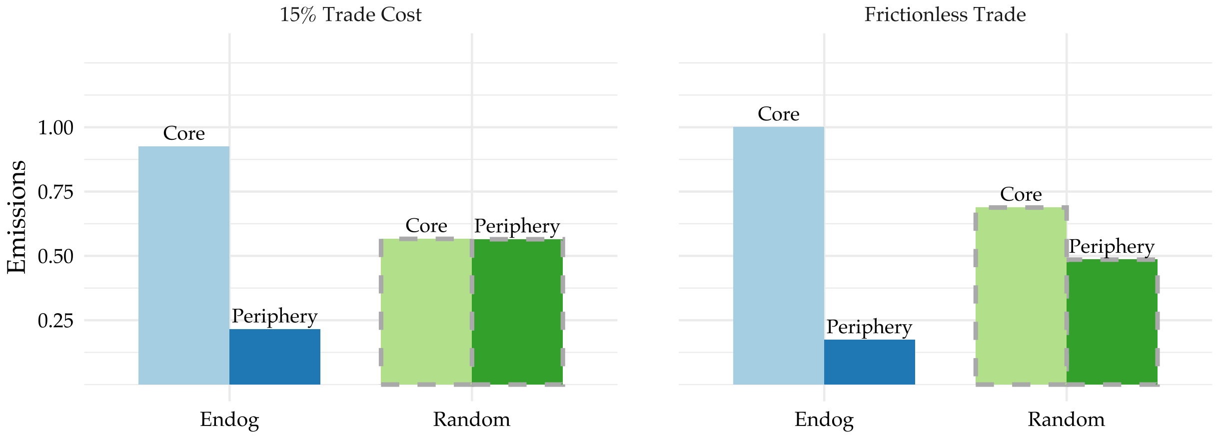
[37] Firms in the core also expand their abatement investments (even though the proportion of such investments decreases).

[38] This finding should not be misinterpreted as indicative of a pollution haven effect, as we maintain consistent environmental regulations in both countries. Our model underscores that the phenomenon of pollution offshoring or outsourcing, especially from regions housing efficient firms, arises due to the interplay of endogenous production networks.

Figure 10: Trade Liberalization and Regional Environmental Accounts

(a) Regional Emissions and Production Networks



(b) Regional Emissions Intensity and Production Networks

Notes: Panel (a) and (b) respectively depict regional emissions and regional emission intensity in the endogenous versus random network regimes under a 15% international trade cost and frictionless international trade.

matching. This causes the periphery region to benefit from a positive environmental spatial spillover effect. This channel is limited in the random network regime in which supply chains are established randomly, rather than optimally.

5 Conclusion

We develop a model to analyze the relationship between inter-firm trade and regional environmental outcomes, focusing on the impact of globalization on spatial disparities in environmental quality. Our analysis aligns with three stylized empirical observations. First, we document that firms tend to collocate in regions with better access to international markets and foreign suppliers (core regions). Second, core regions have higher emission levels yet exhibit lower emission intensities even when accounting for regulatory and industrial differences. Second, firms in core regions possess a greater ability, relative to those in periphery regions, to outsource their emissions via input sourcing from foreign and domestic suppliers. We demonstrate that reduced barriers to international trade in conjunction with the presence of inter-firm linkages results in a higher concentration of pollution in core regions due to increased firm collocation (as well as the scale of production). However, core regions achieve lower emission intensities through greater outsourcing and abatement investments, leading to improved environmental efficiency. We also capture the presence of a positive environmental spatial spillover effect arising from globalization which helps the periphery region to improve its emission intensity. Our modeling framework thus captures a number of important features of the relationship between economic geography, globalization, and environmental quality, features which have to date remained largely under-explored in the literature.

In addition to the central findings of our analysis, our results speak to a number of important policy insights. First, our model challenges the pollution haven hypothesis by taking into account gains from intermediates and the cost of firm-to-firm matching, both of which discourage the relocation of production to pollution-haven countries.[39] Second, our findings suggest that, by lowering inter-regional trade costs, improvements in domestic transportation infrastructure can contribute to lower emission intensities by improving firms' production efficiency and facilitating the sourcing of inputs from regions with a comparative advantage. Additionally, such infrastructure improvements can encourage cleaner firms to establish themselves in the periphery regions, leading to an overall reduction in emission intensity.

We conclude by acknowledging a limitation of our paper. Our analysis assumes that emissions are solely generated through the use of pollution-intensive inputs. However, in reality, pollution is emitted throughout the entire manufacturing process, and the role of intermediate goods in generating pollution emissions has not been examined in our study. If certain types of intermediate goods are particularly emissions-intensive in being transformed into output, outsourcing activities may not necessarily lead to a reduction in total emissions for firms, and the impact of outsourcing on reductions in emissions that we describe may be attenuated. Thus, future research should consider the effect of domestically and globally-sourced intermediates that are heterogeneous in pollution content on environmental quality to provide a more comprehensive understanding of this issue.

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[39] Endogenous production networks imply there are environmental efficiency gains from matching with more efficient foreign suppliers following reductions in trade costs, lowering global emission intensities. This result contrasts with the pollution haven hypothesis.

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