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Regional Environmental Quality and International Trade: The Role of Production Networks

Doyoung Park
Jacob Howard
University of Colorado Boulder

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Department of Economics

University of Colorado Boulder
Boulder, Colorado 80309

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Doyoung Park† and Jacob Howard‡

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Abstract

This paper studies the interaction between trade liberalization and firm production networks in shaping spatial differences in environmental quality within countries. We first analyze the effect of inter-firm trade in intermediate goods on the level of total regional emissions and average emission intensities. Second, we study the effect of trade liberalization on the spatial distribution of firms within countries in a setting with inter-firm production networks. We find that regions with relative proximity to foreign markets attract more firms as international trade barriers diminish. This leads to higher total emissions in such regions due to agglomeration forces, whereas spatial selection together with production networks leads to a decline in average emission intensities.

JEL classification codes: D85, F18, F64, Q53
Keywords: Production networks, Globalization, Outsourcing, Regional environmental quality

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†Department of Economics, University of Colorado Boulder, Email: Doyoung.Park@colorado.edu
‡Department of Economics, University of Colorado Boulder, Email: jacob.b.howard@colorado.edu

1 Introduction

Environmental data both in the U.S. and China suggest that regions with relative proximity to foreign markets exhibit greater total emissions but lower emission intensities.[1] Examining the mechanism behind these two observations in a globalizing world is essential for understanding how environmental and trade policy shape regional heterogeneity in environmental quality and economic activity.

This paper studies and quantifies the role of firm-to-firm production networks in determining abatement investment, total emissions, emission intensities, and spatial distribution of firms in open economies with active environmental policy. For that, we build a quantitative general equilibrium model that captures two important stylized facts observed in the data. First, firms are increasingly connected via complicated production networks,[2] which allows them to reduce their emissions by outsourcing production to other firms. Second, firms tend to concentrate in regions where they can minimize shipping costs to foreign markets. We calibrate the model and conduct a series of counterfactual experiments to quantify the effects of globalization and environmental policy on the level of total emissions as well as emission intensities across different regions within countries.

To study how the regional-level environmental accounts are determined in the context of production networks, we investigate how firm-specific emissions and emission intensities are affected when firms are linked via networks. To do this, we explore how firms optimally choose the levels of abatement investments and outsourced production inputs in response to environmental regulations when they are allowed to establish production relationships with other firms. We additionally show how the interconnected firms choose their locations following globalization. We finally demonstrate how the regional differences in total emissions and emission intensities are determined by globalization.

This paper first finds positive relationships between network intensity, the levels of abatement investments and total emissions. If 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,

[1]The two countries are the world's largest economies that lie on different parts of the income distribution. Section 2 describes these stylized facts in more detail.

[2]Production networks allow firms to seek out the most cost-effective source of intermediate inputs. Production of Boeing's 787 Dreamliner, for instance, sources airplane parts from no less than 50 "tier-1" supplier firms; these tier-1 suppliers themselves source parts from their own "tier-2" suppliers in an elaborate network of intermediate production.

firm-level emissions increase due to the enlarged scale of firms' production activities. This scale effect encourages firms to invest in abatement, and the improved profitability arising from networks allows firms to bear greater abatement costs. However, the effect of abatement investments on reducing total emissions can be attenuated because firms' consumption of carbon-intensive inputs expands due to the drop in effective factor prices due to abatement efforts.

Second, we discover a negative relationship between network intensity and emission intensities. Robust relationships with other firms facilitate the replacement of emission-intensive inputs to outsourced intermediate goods. This enables larger, more efficient firms to lower their emission intensities because their outsourcing activities significantly constrain the increase of total emissions arising from the augmented scale of output production. Smaller, less efficient firms tend to exhibit greater emission intensities compared to larger firms. This is not just due to the smaller scale of output of these less efficient firms, but also because of their portfolio of efforts to reduce total emissions. Because of the limited scope of the networks of smaller firms, abatement investments act as the main channel through which total emissions can be reduced.

Third, we demonstrate that globalization and firm linkages can be driving forces of coastal agglomeration of firms. Trade liberalization incentivizes larger, more productive firms to relocate to coastal regions that grant the easiest access to foreign markets and raises the likelihood that these firms are able to establish production relationships with foreign firms. The existence of firm-to-firm networks magnifies the agglomeration force by encouraging relatively small firms to follow larger firms to the coastal regions where the benefits from domestic inter-firm trade can be maximized. As a result, the number of firms located in such regions increases and the density of firm-to-firm network increases in response to globalization.

In light of this mechanism, this paper finally shows that trade liberalization causes a divergence in environmental quality between inland and coastal regions. The coastal regions experience an increase in their total emissions compared to inland areas due to (a) firms' agglomeration towards the coast, and (b) the expanded scale of production arising from connections between firms. The emission intensities of the coastal regions, on the other hand, are lower than those of the interior regions because of the firm-to-firm intermediate good trade facilitated by the existence of more-robust production networks in the coastal regions.[3]

[3] While inland firms rely mostly on abatement investments to reduce emissions, coastal firms are able to reduce the size

It is important to focus on the role of production networks in our analyses because it captures one of the crucial channels through which globalization affects spatial distribution of firms and regional environmental accounts. We show how the agglomeration forces differ when production networks do not exist. In the absence of networks, the spatial sorting of firms is limited to the most productive and largest firms. However, when firms are connected via networks, the changes in geographical locations of larger firms directly affect the relocation decisions of smaller firms which, in turn, magnifies the coastal agglomeration. This fact implies that the effect of globalization on coastal emissions is underestimated if the network channel is missing in the analysis. Emission intensities, on the other hand, are exaggerated if the production networks are ignored since a large part of firm efforts to lower emissions from outsourcing intermediate inputs is neglected, and only the role of abatement investments is considered.

This paper is related to several strands of literature. First, the model we introduce in this paper captures firm heterogeneity with regard to the utilization of different kinds of production inputs and studies the environmental consequences of this feature in the wake of trade liberalization (e.g., Barrows and Ollivier, 2016; Konishi and Tarui, 2015; Kreickemeier and Richter, 2014; Baldwin and Ravetti, 2014). Past studies found that one of the channels through which trade liberalization improves environmental quality is the exit of the least productive firms, which leads to the reallocation of market share to the most efficient firms: a so-called market share reallocation effect. This paper extends the discussion of the past literature by implementing a framework introduced in Lim (2017), in which firms are heterogeneous along two dimensions: the efficiency with which they utilize production inputs, and the idiosyncratic demand for their output. This setup enables us to not only capture the market share reallocation effect of trade liberalization, but also to study the endogenous formation of firm-to-firm networks, and thus capture the way in which firms outsource their intermediate inputs. The major contribution of this paper is thus that the role of production networks as one of the channels through which globalization influences environmental quality is studied.

Second, this paper is in line with the literature on firms' decisions with regard to the optimal level of abatement investment as a way of minimizing emission tax payments (e.g., Gutiérrez and Teshima,

of their abatement investments in favor of outsourcing intermediate production, which directly results in a decline in coastal emission intensities.

2018; Forslid et al., 2015; Shapiro and Walker, 2015; Forslid et al., 2011 and many others). The difference between this paper and the previous literature is that we consider abatement investments of firms in the context of production networks. We find that larger and more productive firms invest in abatement more intensively than do smaller and less efficient firms. However, the existence of firm-to-firm linkages enables larger firms to reduce the size of their abatement expenditure in favor of outsourcing intermediate production to other firms. In other words, outsourcing activities serve a crucial role in constraining the increase of firms' total emissions alongside the role played by abatement investments when firm-to-firm connections are considered.

Third, this paper relates to a broad research area on the outsourcing activities of firms and its impact on environmental quality. Cole et al. (2017) and Li and Zhou (2017) empirically demonstrate that outsourcing intermediate production from abroad has the effect of reducing firm-level emission intensities, total emissions, and abatement expenditures. However, the outsourcing behaviors of firms in this literature are induced by heterogeneity in environmental regulations across countries; firms outsource intermediate production to foreign markets with relatively lax environmental policies. This paper, on the other hand, finds that outsourcing of intermediates still occurs even when environmental regulations are the same across countries in a context where firms able to establish production networks. This paper further studies the outsourcing activities of firms across regions within the same country. The regional heterogeneity of firms' outsourcing activities is an important element of Feng et al. (2013). Using inter-provincial input-output data, Feng et al. (2013) empirically analyze how coastal firms in China outsource CO_2 (as embodied in outsourced production inputs) from inland firms. However, the authors do not provide any sort of theoretical mechanism considering network formation as a channel that underlies this outsourcing behavior. To fill this gap, this paper explicitly models the endogenous establishment of production networks.

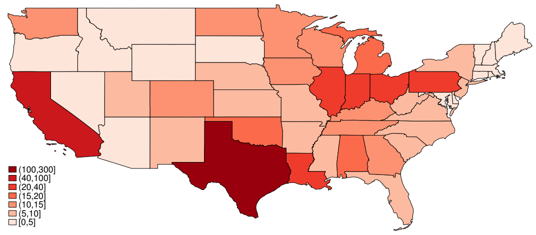
Lastly, this paper is associated with the literature on spatial sorting induced by trade liberalization. Guo (2016), Coşar and Fajgelbaum (2016), Tong (2015), Forslid and Okubo (2015) and Okubo et al. (2010) each show that in response to market integration, productive firms relocate to markets (domestic or foreign) that offer the greatest access to large bases of consumers. In particular, Guo (2016) demonstrates that China's accession to the World Trade Organization (WTO) in 2001 spurred the agglomeration of firms towards coastal provinces. This paper also studies the effect of market integration on the spatial sorting of firms towards coastal regions where firms have the easiest access to foreign markets. Miyauchi (2017) reveals that firm-to-firm matching is one of the forces inducing the agglomeration of firms. We extend this work by modelling the interplay of globalization and firm-to-firm linkages as the main driving forces in the coastal agglomeration of firms. More importantly, this paper extends the discussion to study its implications in determining regional environmental quality.[4]

The remainder of the paper is organized as follows. Section 2 shows that coastal regions in the United States and China experience greater total emissions, but comparatively lower emission intensities than interior regions. Motivated by these phenomena, Section 3 investigates the role of production networks in determining firms' environmental accounts together with their location decisions between inland and coastal regions. In Section 4, we conduct numerical exercises to quantify the findings from Section 3. Section 5 concludes.

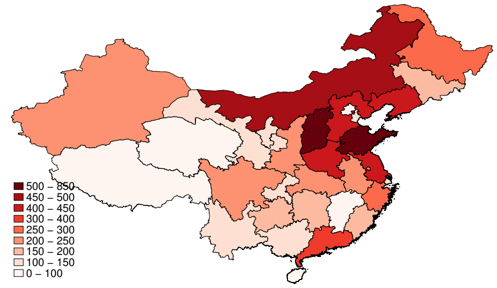
2 Motivating Evidence

We provide interesting stylized facts consistently observed in the U.S. and China. We first pay attention to the fact that, within both the U.S. and China, a greater share of emissions is generated in the coastal regions compared to the interior regions. Second, we capture the fact that coastal regions exhibit relatively lower emission intensities than interior regions. We find a strong positive correlation between coastal concentration of total emissions and spatial distribution of

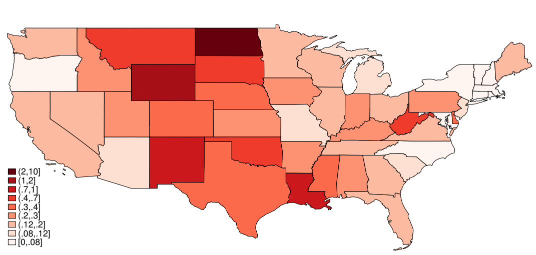
[4]There have been numerous attempts to explore the intersection between the openness of an economy and the environmental quality. For example, Antweiler et al. (2001), Levinson (2009), Grether et al. (2009) and Shapiro and Walker (2015) argue that the openness of an economy plays almost no role in determining emission intensities. These works argue that the country- and industry-level improvements in air quality observed in recent years are mainly due to the use of more efficient production processes (the "technique effect"), mostly arising from stricter environmental regulations. Barrows and Ollivier (2016), however, find that the trade-induced industrial composition effect was as large as the technique effect in the time period of their studies; freer trade changed the composition of industries and thus played a crucial role in reducing emissions. As firm- and even plant-level micro-data are increasingly available, more evidence has been proffered in line with Barrows and Ollivier (2016). Recent studies explore whether the export status of a firm or trade liberalization have positive effects on reducing the emission intensities of firms/plants. Holladay (2016) and Cui et al. (2015), for instance, show that exporting firms are on average cleaner than non-exporters since exporters are more productive. Forslid et al. (2015) also derive a similar result that exporting firms are cleaner than non-exporters as exporting firms have higher incentives to undertake larger abatement investments. Approaching from a slightly different angle, Martin (2011) and Cherniwchan (2017) respectively study the effect of import tariff reductions on firm-level and plant-level emission intensities in India and in the U.S. Both studies discover that trade liberalization leads to a reduction in emission intensities, and an improvement in air quality. Despite the existence of meaningful findings in this existing literature, there have yet been few attempts to explain regional differences in environmental quality that arise because of trade liberalization. Furthermore, the interaction of trade liberalization and firm production networks in determining environmental quality has been under-appreciated in the past studies.



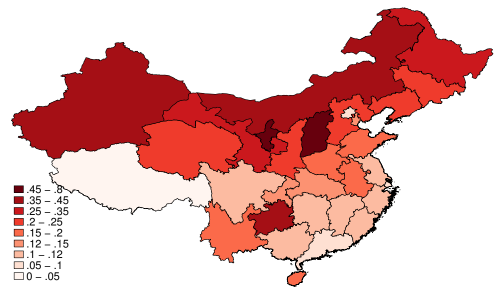
(a) Distribution of carbon emissions both in the U.S. (2015)



(b) Distribution of carbon emissions in China (2010)



(c) Distribution of emission intensities in the U.S. (2015)



(d) Distribution of emission intensities in China (2010)

Figure 1: The heterogeneous distribution of total carbon emissions and regional emission intensities

firms towards the coastal regions.[5] We additionally find that coastal firms in the U.S. and China are net importers of carbon-dioxide (CO_2) embodied in the domestically transacted intermediate commodities.[6] This paper incorporates these facts and propose one of the mechanisms which induces a greater concentration of pollution emissions, but lower emission intensities in the coastal regions.

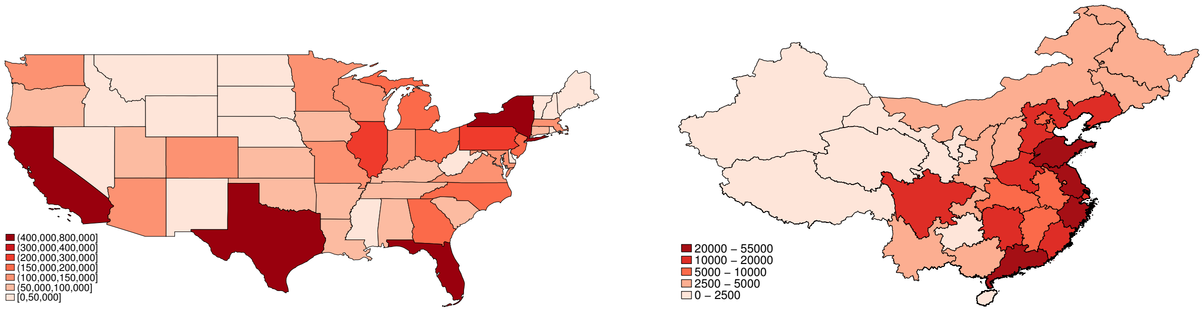
2.1 The Heterogeneous Distribution of Carbon Emissions and Emission Intensities between Coastal and Inland Regions

This paper is motivated by the heterogeneous distribution of pollution emissions and regional emission intensities, both of which can be seen in the U.S. and China.[7] For example, from Figures 1a and 1b, we consistently observe that carbon emissions are concentrated in the coastal regions whereas Figures 1c and 1d tell us that interior areas experience relatively higher emission levels

[5] Statistics of U.S. Businesses(2013) and China Above Scale Industrial Firm Panel (2007) data support this argument.

[6] This fact is observable from the input-output data in China (2007) used by Feng et al. (2013), and the commodity flow survey in the U.S. (2012).

[7] We pick the two countries because they are the two of the world's largest economies. Furthermore, the U.S. is a developed country while China is a developing country. Interestingly, they both exhibit the same features.



(a) Coastal concentration of firms in the U.S. (2013) (b) Coastal concentration of firms in China (2007)

Figure 2: Distribution of firms in the U.S. and China

per value-added (output), which we call emission intensities.[8][9] In other words, coastal states in the U.S. and coastal provinces in China are cleaner per unit of output compared to inland regions even though most polluting activity takes place on the coast.[10]

We pay particular attention to the coastal agglomeration of firms as one of the main causes inducing the concentration of carbon emissions near the coast as firms are the main economic agents emitting CO_2; the Environmental Protection Agency (EPA) reports that the industrial sector was responsible for 22% of total greenhouse gas emissions in 2016, and 81% of those were the emission of CO_2. Figure 2 shows that a majority of firms are agglomerated on the East and West Coasts, as well as the Great Lakes which is positively correlated with the distribution of CO_2 emissions across states. We also observe a similar pattern in China. A large number of firms are concentrated in the coastal provinces, and the distribution of firms is consistent with the greater coastal CO_2 emissions illustrated in Figure 1b.

The location of firms may, at least in part, provide us with a reasonable explanation for greater total CO_2 emissions in the coastal areas; however, it is still insufficient to explain why we observe relatively lower emission intensities near the coast.[11] We thus study a potential channel through

[8]The unit of CO_2 emissions in the U.S. is million metric ton, while that of China is million tonnes. The unit of CO_2 emission intensity in the U.S. is million metric ton of CO_2 per billion chained 2009 dollars whereas that of China is million tonnes of CO_2 per 1 billion yuan.

[9]Figures 1a and 1c describes CO_2 emissions, emission intensities of U.S. non-energy intensive manufacturing sector; however, Figures 1b and 1d depict CO_2 emissions, emission intensities in Chinese provinces without specified sector due to lack of data availability.

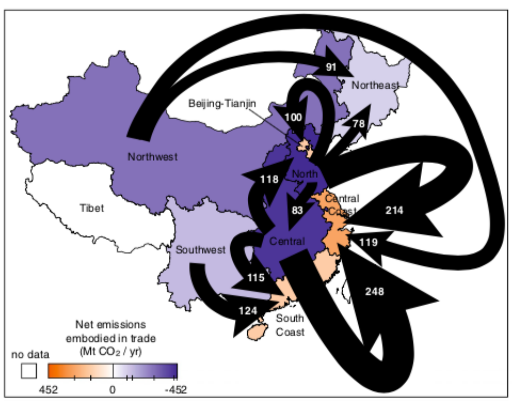
[10]Appendix A shows the time consistency of these contrasting patterns.

[11]One argument might be that greater value-added in the coastal regions induced by agglomeration of firms leads to lower emission intensities in these regions: productive and large firms are selected to exist (relocate) in (towards) the coastal market (i.e., the composition effect). However, accounting for the fact that total emissions also generally increase along with the scale of production, the question as to which factors cause the total CO_2 emissions to expand at a lower rate than total value-added remains unanswered.

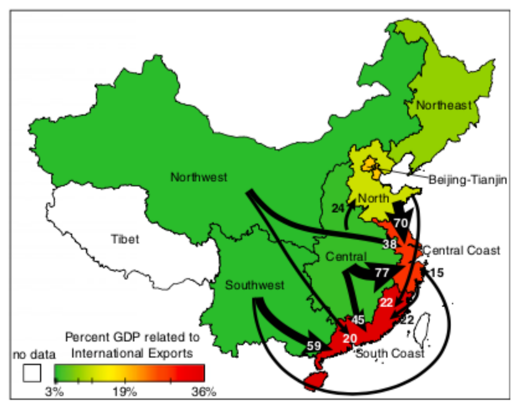
which coastal firms reduce their total emissions but increase the production level.

2.2 Networks and Emission Intensity

We turn our attention to inter-regional embodied CO_2 flows both in the U.S. and China in order to explore one of the possible reasons behind the heterogeneous distribution of emission intensities between the coast and inland. Feng et al. (2013), for example, empirically demonstrate that CO_2 emissions in the coastal provinces in China are outsourced from inland provinces (Figure 3a). In addition, the authors show that international trade leads to unidirectional flows of CO_2 emissions embodied in intermediates for exports (Figure 3b). Even though the analysis in Feng et al. (2013) is conducted at the province level, the implication still holds that outsourcing of intermediate inputs from inland supplier firms may have the effect of reducing coastal firms' total emissions and thus their emission intensities for a given level of output, because otherwise these intermediates would have been produced in the coastal regions.



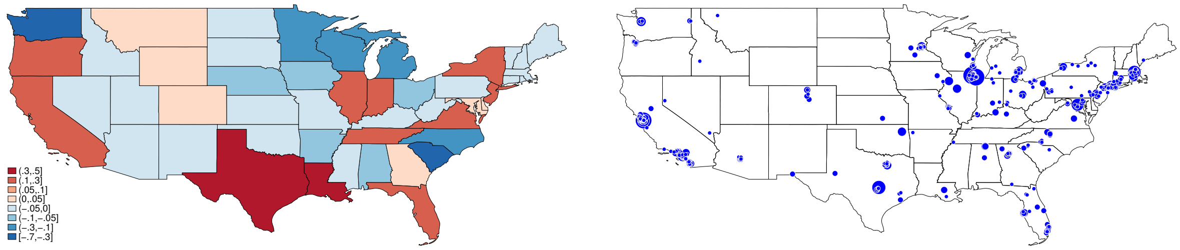
(a) Interprovincial CO_2 flows in China (2007)



(b) Interprovincial CO_2 flows embodied in goods for international exports (2007)

Figure 3: Flows of carbon dioxide by interprovincial outsourcing in China (Feng et al., 2013)

Similar patterns are observed in the U.S. We study the inter-state flow of CO_2 (million metric ton per 2009 chained dollar) using the Commodity Flow Survey (CFS, 2012) and industrial emission data obtained from the U.S. Energy Information Administration (EIA). Figure 4a portrays that coastal states are overall net importers (illustrated in red) of CO_2 whereas inland states are, in



(a) U.S. states as net exporters or importers of embodied CO_2 (2012)

(b) Coastal concentration of U.S. firms and their sizes by total number of trade partners (2007)

Figure 4: Flows of CO_2 by interstate outsourcing in the U.S.

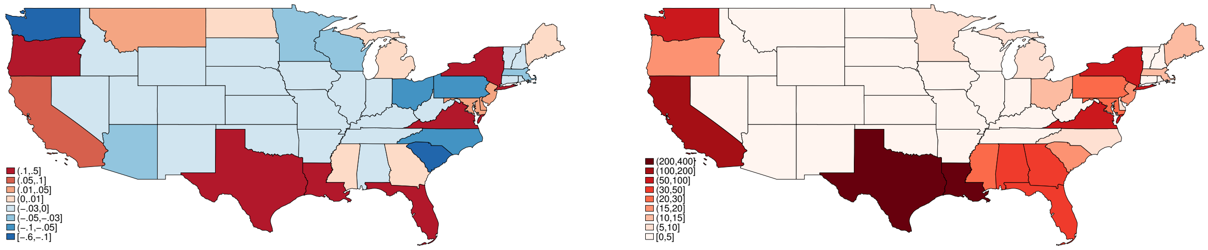
general, net exporters (colored in blue).[12][13] This implies that commodities are, on average, flowing from the inland regions to the coast where firms are concentrated and firm-linkages are formed. Figure 4b describes the location of headquarters of U.S. firms and the coastal agglomeration of firm networks by illustrating the total number of trade partners of each firm (with the size of the networks shown by the size of the bubbles).[14] Figure 5a supports Figure 4a. It depicts that CO_2 embodied in intermediates for international exports is transported to the coastal states where the major ports are located. Figure 5b shows the total foreign trade volume (tonnage) by each state,[15] and we are able to verify that the foreign trade volume is positively correlated with the influx of CO_2 into the coastal regions.

[12] There are exceptional coastal states (e.g., Washington, North and South Carolina) as net exporters and inland states (e.g., Colorado, Wyoming and Montana) as net importers of embodied CO_2, yet we still observe the general pattern that CO_2 is embodied in commodities transported towards the coastal regions.

[13] The CFS (2012) data provide origin and destination states of commodity flows together with the NAICS code and shipment values. We focus on the commodity flow data in the (relatively) non-energy intensive manufacturing sector; data with the NAICS code greater than 400, or under 300 are excluded; and within the manufacturing sector, data are dropped if the NAICS code is equal to 324 (Petroleum and Coal Products Manufacturing), 325 (Chemical Manufacturing) and 326 (Plastics and Rubber Products Manufacturing). We capture the fact that CO_2 emissions are typically in proportional to the value-added in the manufacturing sector. We calculate adjusted total CO_2 emissions from non-energy intensive manufacturing sector in 2012 using data from Environmental Information Administration (EIA) and Bureau of Economic Analysis (BEA). We also obtain the share of value-added by each shipment of commodities from total value-added generated in 2012. Using these information, we measure CO_2 emissions exported from and imported to each state, which finally determines the net exporting and importing U.S. states of CO_2.

[14] We use Compustat data to derive the figure. One of the caveats of using the Compustat database is that it only reports the trade partners who account for more than 10% of the selling firms' revenue. In other words, relationships between small firms or between large and small firms can be underreported or even missing. However, we are still able to observe that major firms are concentrated near the coast and coastal firms have an overall higher number of trade partners than inland firms.

[15] The data are from Port Industry Statistics. Click the following link for more detail: U.S. Port Rankings by Cargo Tonnage 2015.



(a) U.S. states as net exporters or importers of embodied CO_2 for international exports (2012)

(b) Total foreign trade volume by state (2013)

Figure 5: Firm-level networks and the location of ports in the U.S.

We have thus far explored the possibility of reducing CO_2 emission intensity in the coastal regions through the outsourcing of intermediates from the illustration of CO_2 flows embodied in commodities transacting across states.[16] It is still unclear, however, which determines the direction of outsourcing. Why is the direction of the net flow of commodity (and thus embodied CO_2) from the inland to the coast, not the other way around? In order to find a plausible answer for this question, we study the effect of globalization on the agglomeration of firms towards the coast.

2.3 Networks and Economic Geography

Considering the facts that firms are, in general, agglomerated in the coastal regions, and these coastal regions are net importers of commodities reflecting embodied CO_2, we shift our focus to studying the underlying reasons for the heterogeneous distribution of firms across regions, and the net influx of commodities from inland to the coast. Guo (2016), for example, explores the role of trade cost reductions on firms' agglomeration towards the coast in China. He shows that the country's accession to the WTO in 2001 caused the number of firms in coastal provinces to increase.[17] Lim (2017) provides an important theoretical framework describing the establishment of

[16] Recent literature provides empirical evidence demonstrating the effect of outsourcing intermediate production on firm-level total emissions, abatement investments and emission intensities, each of which in turn affect regional emission intensities. For example, Cole et al. (2017) find that (foreign) outsourcing activities by Japanese firms (2009-2013) have reduced the growth of CO_2 emission intensity by 5.1% in the year when firms began outsourcing. Li and Zhou (2017) also show that a 10% point increase in (foreign) outsourcing of emission-intensive inputs by U.S. manufacturing parent firms causes U.S. plants to release 4% less toxic material, and in turn saves, on average, $402,000 in abatement costs. Zhang (2015) additionally proves that the impact of energy use on CO_2 emissions is lower in countries evincing a higher degree of trade in intermediate goods.

[17] Nagy et al. (2016)also pay attention to the role of international trade and spatial frictions on locations and formations of cities, and Baldwin and Okubo (2005), Okubo (2009), Okubo et al. (2010) combine Melitz-type heterogeneous firm model to new economic geography model established from Krugman (1991), and theoretically demonstrate that relocations are more likely to take place for relatively large and productive firms: spatial selection. Ottaviano (2010) and Von Ehrlich and Seidel (2013) are in line with this literature, but they study the agglomeration of firms by

firm networks which helps us understand the flow of commodities across firms. He demonstrates that large and efficient firms are increasingly able to establish relationships with other firms thanks to their greater expected profits from the network. Miyauchi (2017) provides an important stepping stone between the two studies. The author reveals that production networks between firms are important channels influencing firms' agglomeration.[18]

This paper incorporates the three literature. We build a theoretical framework showing that trade costs reductions incentivize the most productive (and thus, after the heterogeneous firms literature, exporting) firms to agglomerate towards the coast. The existence of firm linkages encourages smaller firms to follow exporting firms since geographical proximity improves profits from domestic inter-firm trade.Thus, the coastal agglomeration of firms is magnified and commodities are more likely to flow from inland to coastal regions.

The following section introduces the theoretical framework describing the channel through which globalization induce heterogeneous patterns of total emissions and emission intensities between inland and coastal regions.

3 The Model

The model we introduce in this section provides a theoretical framework describing the formation of production networks among firms.[19] We are also conceptually motivated by Guo (2016) who demonstrates the effect of trade liberalization on firms' agglomeration in the coastal region. Combining the two seemingly unrelated topics, we suggest a new framework which illustrates the particular role of firm linkages in inducing the heterogeneous distribution of firms between interior and coastal regions, and in affecting firms' optimal abatement investments, total emissions, and emission intensities after the reduction in international trade costs.

entry and exit of firms, not via relocation of firms. The model we proposed in this paper includes the components of firms' entry/exit problem and the heterogeneity of firms. We further incorporate firm linkages in the economic geography literature.

[18] The author demonstrates that downstream firms (i.e., input buyers) exhibit higher revenue when locating where input selling 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 the upstream firms to agglomerate in the location where they expect a higher matching rate with customers. Even though Miyauchi (2017) suggests an important linkage between Guo (2016) and Lim (2017), it does not provide a clear connection between trade liberalization and the agglomeration of firms towards the coast via the channel of inter-firm networks.

[19] Lim (2017) provides a theoretical foundation of this paper.

3.1 Basic Environment

The economy is comprised of households and monopolistically competitive firms. We denote the set of firms as S_χ; firms are indexed by their characteristics χ. Each firm participating in the supply chain utilizes both emission-intensive inputs, $d(\chi)$, and outsourced intermediates from the upstream χ'-firms, $x(\chi,\chi')$. All firms in the network are assumed to have identical production technology (i.e., a CES production technology with a common elasticity of substitution, σ), which enables us to focus on the cost minimization problem of the representative firm. Each domestic firm receives a random draw of idiosyncratic characteristics $\chi = (\phi, \delta)$ where ϕ refers to firm's fundamental productivity in using emission-intensive inputs, and δ is the fundamental demand for the firm's specific variety of output which influences the "size" of the firm in terms of its total sales. The states of firms, χ, are assumed to follow a cumulative distribution function G_χ with density g_χ.

3.1.1 Households

We assume that the representative household has the following CES preferences over all χ-firms' varieties:

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

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

$$x_H(\chi) = UP_H^\sigma \delta^{\sigma-1} p_H(\chi)^{-\sigma}.$$

such that the consumer price index is given by

$$P_H \equiv \left[\int_{S_\chi} \left(\frac{p_H(\chi)}{\delta}\right)^{1-\sigma} dG_\chi(\chi)\right]^{\frac{1}{1-\sigma}}. \tag{3.1}$$

To make the notation concise, we define a household aggregate demand shifter as $\Delta_H \equiv UP_H^\sigma$, which is common across the demands of the representative household for all varieties: it shifts the household demand for all varieties equally. Therefore, the household's final demand for the variety produced by χ-firm can be simply re-written as:

$$x_H(\chi) = \Delta_H \delta^{\sigma-1} p_H(\chi)^{-\sigma}. \tag{3.2}$$

3.1.2 Firm Production Technology

Similar to Lim (2017), we assume that firms produce their outputs by utilizing carbon-intensive inputs and intermediate goods from other firms. However, the outsourcing of inputs takes place under uncertainty in establishing relationships between firms: supplier-consumer relationship is built in a non-deterministic way. Every χ-firm has the probability $m(\chi, \chi')$ of establishing a production network with χ'-firm as the supplier of intermediates; conversely, every χ'-firm faces uncertainty in matching with the customer χ-firm. m denotes the matching function of the firm pair, χ and χ'. The matching function is assumed to be exogenously given in this section; however, we endogenize the matching probability in section 3.4. Given the uncertainty in matching, we are able to introduce the CES output production function of the χ-firm as the following:

$$X(\chi) = \left[[\phi d(\chi)]^{\frac{\sigma-1}{\sigma}} + \int_{S_\chi} m(\chi, \chi') [x(\chi, \chi')]^{\frac{\sigma-1}{\sigma}} dG_\chi(\chi') \right]^{\frac{\sigma}{\sigma-1}}. \tag{3.3}$$

Equation (3.3) portrays the role of ϕ in determining firm-level outputs: as firms are fundamentally efficient in using emission-intensive inputs (i.e., greater ϕ), output productions are strongly sustained by the usage of $d(\chi)$ due to the gross substitutability between production inputs. The utilization of outsourced intermediate inputs takes place through the matching process between firms which again involves uncertainty due to the inclusion of the matching function m. [20]

We additionally consider a carbon emission function as firms emit pollution as byproducts of the production process:

$$e(\chi) = \frac{f\,[d(\chi)]}{h\,[f_A\,(\chi)]}. \tag{3.4}$$

Assuming that f is a monotonically increasing pollution generation function with respect to the amount of emission-intensive inputs (i.e., $f'(.) > 0$), equation (3.4) indicates that greater use of

[20] The input suitability parameter is assumed to be unity throughout the entire paper which indicates that inputs from other firms can be utilized with 100% efficiency. We also assume that α is common across all firms; however, the model can be extended to allow for the existence of different sectors, in which case α would vary across sectors and would be higher if the inputs are relatively more important in the production process.

emission-intensive inputs increases the volume of pollution emissions. However, each χ-firm can expend effort to reduce pollution by investing on abatement, the cost of which is described by the function $f_A(\chi)$. We additionally assume that $h'(\boldsymbol{.}) > 0$, which in turn implies that greater emissions can be reduced via larger abatement investments. Given the prices of production inputs and investing in abatement, the cost minimization problem of the χ-firm – which determines the optimal basket of inputs – can be described as the following:

$$\min_{d(\chi),\{x(\chi,\chi')\}_{\chi'\in S_\chi}} f_A(\chi) + \kappa d(\chi) + \int_{S_\chi} m(\chi,\chi')p(\chi,\chi')x(\chi,\chi')dG_\chi(\chi')$$
$$+ \lambda \left[X(\chi) - \left\{ [\phi d(\chi)]^{\frac{\sigma-1}{\sigma}} + \int_{S_\chi} m(\chi,\chi')\left[x(\chi,\chi')\right]^{\frac{\sigma-1}{\sigma}} dG_\chi(\chi') \right\}^{\frac{\sigma}{\sigma-1}} \right].$$

κ is the unit cost of emission-intensive inputs and $p(\chi,\chi')$ is the unit price of intermediate outputs. We assume that the unit cost of emission-intensive inputs, κ, is comprised of the unit price of inputs, ω, and associated emission tax payments (per unit of emission-intensive input):

$$\kappa = \omega + \frac{te(\chi)}{d(\chi)}. \tag{3.5}$$

Therefore, the marginal cost of production can be illustrated as

$$\eta(\chi) = \left[\phi^{\sigma-1}\kappa^{1-\sigma} + \alpha^{\sigma-1} \int_{S_\chi} m(\chi,\chi')p(\chi,\chi')^{1-\sigma} dG_\chi(\chi') \right]^{\frac{1}{1-\sigma}}, \tag{3.6}$$

while the optimal demands for production factors are given respectively by:

$$d(\chi) = X(\chi)\eta(\chi)^\sigma \kappa^{-\sigma}\phi^{\sigma-1}, \tag{3.7}$$

$$x(\chi,\chi') = X(\chi)\eta(\chi)^\sigma p(\chi,\chi')^{-\sigma}. \tag{3.8}$$

3.1.3 Market Clearing and the Optimal Pricing Strategy

The optimal demand for emission-intensive inputs and intermediate varieties from the supply firms in the network enable us to consider the market clearing conditions as the following:

$$D = \int_{S_\chi} d(\chi) dG_\chi(\chi), \tag{3.9}$$

$$X(\chi) = x_H(\chi) + \int_{S_\chi} m(\chi', \chi) x(\chi', \chi) dG_\chi(\chi'), \tag{3.10}$$

which respectively illustrate that the total amount of emission-intensive inputs, D, and intermediates, $X(\chi)$, are the sum of each individual firms' demand for the production factors.

Since all firms in the production network are assumed to participate in a monopolistically competitive market, we also need to consider the optimal pricing scheme of firms given the optimal demand for intermediate varieties by the household as well as customer firms. Firms in the supply chain choose the price of their intermediate outputs which maximizes their profits.We are able to verify that monopolistically competitive firms charge prices with constant markups on top of the marginal costs of production:

$$p_H(\chi) = p(\chi', \chi) = \mu\eta(\chi), \tag{3.11}$$

where $\mu = \frac{\sigma}{\sigma-1}$, which is the markup of a monopolistically competitive firm where σ is the elasticity of substitution between emission-intensive production factors and outsourced intermediate outputs.

3.2 Equilibrium of the Model

3.2.1 The Characteristics of a Firm's Network

Recall that firms participating in the production network can be characterized by their fundamental productivity, ϕ, and demand, δ. In order to deepen our understanding for the characteristics of the production networks, we adopt two concepts from Lim (2017), so-called the *network demand,*

$\Delta(\chi)$, and the *network productivity,* $\Phi(\chi)$:

$$\Delta(\chi) \equiv \frac{1}{\Delta_H} X(\chi)\eta(\chi)^{\sigma}, \tag{3.12}$$

$$\Phi(\chi) \equiv \eta(\chi)^{1-\sigma}. \tag{3.13}$$

The network demand of the χ-firm indicates the value of intermediate outputs consumed by downstream firms in the network compared to that by the representative household. Equation (3.12) describes that greater total sales implies higher network demand by intermediate firms. The network productivity is intuitively more straightforward. Equation (3.13) depicts that the network efficiency of the χ-firm improves when intermediate goods from other firms are obtainable at lower prices.

Combining equations (3.6), (3.7), (3.8) and (3.11), we are able to derive the following expressions for network demand and network productivity:[21]

$$\Delta(\chi) = \mu^{-\sigma}\delta^{\sigma-1} + \mu^{-\sigma}\int_{S_\chi} m(\chi', \chi)\Delta(\chi')dG_\chi(\chi'), \tag{3.14}$$

$$\Phi(\chi) = \phi^{\sigma-1}\kappa^{1-\sigma} + \mu^{1-\sigma}\int_{S_\chi} m(\chi, \chi')\Phi(\chi')dG_\chi(\chi'). \tag{3.15}$$

Given a matching function (i.e., firms observe the characteristics of other firms and, given these characteristics, the probability to be matched is fixed), equation (3.14) tells us that the network demand of the supplier χ-firm is affected by the fundamental demand of the firm together with the network demands of each of the customer firms with which the χ-firm has established a production network. This implies that the network demand of a firm can be improved by establishing networks with larger, or a higher number of, downstream firms. Equation (3.15) can also be interpreted in a similar manner. The network productivity of the χ-firm is determined not only by the fundamental productivity of the firm, but also by the network productivities of its supplier firms. Customer firms are able to improve their network efficiencies by outsourcing intermediate inputs from efficient upstream firms in the network which produce intermediates at lower prices.

[21] See Appendix for the detailed derivation.

3.2.2 Firm Size and Firm-to-Firm Trade

As documented in Lim (2017), the network characteristics of a firm enable us to easily calculate the total revenue, $R(\chi)$, variable profit, $\pi(\chi)$, variable emission-intensive input, $d(\chi)$ and bilateral intermediate input, $x(\chi, \chi')$, consumption, and finally the total scale of production, $X(\chi)$:

$$R(\chi) = \mu\Delta_H\Delta(\chi)\Phi(\chi), \tag{3.16}$$

$$\pi(\chi) = (\mu - 1)\,\Delta_H\Delta(\chi)\Phi(\chi), \tag{3.17}$$

$$d(\chi) = \Delta_H\Delta(\chi)\kappa^{-\sigma}\phi^{\sigma-1}, \tag{3.18}$$

$$x(\chi, \chi') = \mu^{-\sigma}\Delta_H\Delta(\chi)\Phi(\chi')^{\frac{\sigma}{\sigma-1}}. \tag{3.19}$$

and

$$X(\chi) = \Delta_H\Delta(\chi)\Phi(\chi)^{\frac{\sigma}{\sigma-1}}. \tag{3.20}$$

We can verify that the revenue and variable profit of a firm are crucially determined by the firm's network characteristics. Firms in the network are able to achieve greater revenue and profits when they obtain production inputs at lower prices and sell their variety of products to more number of, and larger customer firms. The emission-intensive input consumption by a firm is determined by three channels. First, the network demand for intermediate inputs by the household and customer firms affects the quantity of emission-intensive input consumed by a firm because the network demand directly influences the scale of production. Second, the input price negatively affects the quantity demanded of emission-intensive input. Lastly, the fundamental efficiency in utilizing emission-intensive input determines the input consumption by a firm; if a firm is productive in using emission-intensive input, then the firm is more inclined to substitute intermediate inputs to emission-intensive input. The intermediate input demand and the total output production are affected by the network demand by the household and firms, which again due to its effect on altering the total scale of production. Additionally, the consumption for intermediate inputs is crucially influenced by the network efficiency of the supplier firm. In other words, the quantity demanded for the intermediates by the consumer firm increases as the supplier firm provide intermediate outputs at lower prices; if the upstream firm is productive, the firm is able to provide its own variety at a lower price due to small marginal costs of production. The total output production is also determined by the network efficiency of a firm. The production activity of a firm is encouraged when the prices of production factors are low.

3.2.3 Household Demand Shifter, Price Index and Welfare

From the market clearing equation (3.9), and equation (3.18) which describes the optimal demand for emission-intensive inputs, we are able to obtain an expression for the household demand shifter given by

$$\Delta_H = \frac{D}{\int_{S_\chi} \Delta(\chi)\kappa^{-\sigma}\phi^{\sigma-1}dG_\chi(\chi)}. \tag{3.21}$$

Equation (3.21) portrays that the household demand for intermediate varieties increases as the endowment of emission-intensive inputs expanses. This is because the production activities of intermediate outputs by firms are supported by increased availability of production inputs. The equation further illustrates that the household demand for the produced varieties is negatively affected by the demand from intermediate firms; the two economic agents are competitors in obtaining intermediate outputs. The unit price of emission-intensive inputs also affects the household demand shifter. When the factor price increases, the marginal cost of production also increases, which in turn reduces the consumption of intermediates by firms due to their diminished scale of production. Thus, the household demand relatively rises. The greater fundamental efficiency, however, reduces the relative household demand because it encourages firms' production activities, which in turn induces greater share of intermediate outputs to be allocated towards firms in the network.

We can additionally obtain the price index of the household and the welfare level from equation (3.2) and the definition of household demand shifter, $\Delta_H = UP_H^\sigma$, as the following:

$$P_H = \mu\left[\int_{S_\chi} \Phi(\chi)\delta^{\sigma-1}dG_\chi(\chi)\right]^{\frac{1}{1-\sigma}} \tag{3.22}$$

$$U = \frac{D\mu^{-\sigma}\left[\int_{S_\chi} \Phi(\chi)\delta^{\sigma-1}dG_\chi(\chi)\right]^{\frac{\sigma}{\sigma-1}}}{\int_{S_\chi} \Delta(\chi)\kappa^{-\sigma}\phi^{\sigma-1}dG_\chi(\chi)}. \tag{3.23}$$

The message of equation (3.22) is straightforward. As firms become more efficient, the household can purchase intermediate goods at a lower price. This implies that the "price" for obtaining an additional unit of utility diminishes. The fundamental demand parameter possesses a similar implication. If the household initially possesses stronger preference on intermediate varieties (i.e., greater fundamental demand), it indicates that the "cost" the household needs to bear in order to obtain one unit of utility decreases. We can reverify these arguments from equation (3.23). Equation (3.23) illustrates that greater household demand induces higher level of utility as well as the reduction of price index arising from firms' improved network efficiency and larger fundamental demand escalates the utility level of the household.

3.3 Optimal Investment in Abatement and Firm-level Emission Intensities

In this section, we study how firm linkages influence firms' optimal investment on pollution abatement, and the ensuing impact on firms' emission intensities. At this point, we have derived all of the necessary relationships needed to study firms' abatement efforts except for the specific functional form of the pollution generating process. We thus introduce a simple but straightforward functional form that characterizes the production of pollution emissions, and further explore how the optimal level of abatement will be decided by firms. To make our model tractable, but without losing generality, we assume that the χ-firm's pollution emissions are proportional to the demand for emission-intensive inputs, and the pollution emissions can be monotonically reduced by the abatement investments, $f_A(\chi)$:

$$e(\chi) = \frac{\epsilon d(\chi)}{f_A(\chi)}. \tag{3.24}$$

$\epsilon > 0$ is a scale parameter (i.e., carbon conversion parameter) which reflects the marginal effect of emission-intensive inputs on pollution emissions; the emission of carbon dioxide is mainly determined by the carbon content of the fuels that firms utilize. Combining equations (3.5) and (3.24), we can simplify the expression for the unit cost of the emission-intensive input (κ):

$$\kappa = \omega + \frac{t\epsilon}{f_A(\chi)}. \tag{3.25}$$

Equation (3.25) shows that increasing the amount of abatement investments dramatically reduces the "effective price" of carbon-intensive inputs (i.e., the price of the input plus the tax payment) because the tax payments on emissions decrease with more abatement investment.[22] As firms

[22] The significant decline in the price resulting from abatement investments is induced by the convex functional form of emissions production. Increasing abatement investments reduces pollution emissions significantly, which in turn reduces firms' emission tax payments.

determine the level of optimal abatement expenditures that will maximize their total profits, we can consider the following first-order condition:

$$\frac{\partial \Pi(\chi; f_A(\chi))}{\partial f_A(\chi)} = \frac{\partial \eta(\chi)^{1-\sigma}}{\partial f_A(\chi)}(\mu - 1)\Delta_H \Delta(\chi) - 1 = 0,$$

where $\Pi(\chi)$ denotes the total profit of the χ-firm and $\Delta_H \Delta(\chi)$ is the product of network demands of the representative household and intermediate downstream firms for the χ-firm's intermediate outputs. From equation (3.6), we derive the first term of the above equation as

$$\frac{\partial \eta(\chi)^{1-\sigma}}{\partial f_A(\chi)} = t\epsilon(\sigma - 1)\phi^{\sigma-1} \left(\omega f_A(\chi) + t\epsilon\right)^{-\sigma} f_A(\chi)^{\sigma-2} > 0.$$

The above result tells us that the efficiency of the production network increases (i.e., marginal cost diminishes) as abatement investments increase because of the reduction in tax penalties. Substituting this into the firm's first-order condition gives the following implicit function which characterizes the optimal investments on abatement, $f_A^*(\chi)$:

$$\Psi(\chi) \equiv t\epsilon(\sigma - 1)\phi^{\sigma-1} \left(\omega f_A(\chi) + t\epsilon\right)^{-\sigma} f_A(\chi)^{\sigma-2}(\mu - 1)\Delta_H \Delta(\chi) - 1 = 0. \tag{3.26}$$

Given the optimal demand for emission-intensive inputs and the optimal abatement investments respectively derived from equations (3.7) and (3.26), we are able to derive the equilibrium amount of firm-level pollution emissions from equation (3.24):

$$e^*(\chi) = \epsilon\phi^{\sigma-1}\Delta_H \Delta(\chi) \left[\left(f_A^*(\chi)\omega + t\epsilon\right) f_A^*(\chi)^{\frac{1-\sigma}{\sigma}}\right]^{-\sigma}. \tag{3.27}$$

As emission intensity conventionally refers to the pollution emissions per unit of output, the firm–level emission intensities can be calculated by measuring the ratio of total emissions to total output for each firm. Equation (3.20) provides a measure of emission intensities of the χ-firm, $\Xi(\chi)$:

$$\Xi(\chi) \equiv \frac{e(\chi)}{X(\chi)} = \frac{e(\chi)}{\Delta_H \Delta(\chi)\Phi(\chi)^{\frac{\sigma}{\sigma-1}}}. \tag{3.28}$$

The combination of equation (3.28) with equation (3.27) enables us to derive the optimal level of emission intensity of a χ-firm:

$$\Xi^*(\chi) = \epsilon\phi^{\sigma-1}\Phi(\chi)^{-\frac{\sigma}{\sigma-1}} \left[(f_A^*(\chi)\omega + t\epsilon)\, f_A^*(\chi)^{\frac{1-\sigma}{\sigma}} \right]^{-\sigma}. \tag{3.29}$$

Equation (3.29) conveys a clear message that emission intensity goes up as the emission-intensive input possesses higher carbon conversion rate: greater amount of pollution are generated from using one unit of emission-intensive input. The equation also describes that the higher fundamental efficiency of a firm, ϕ, increases emission intensities. This is because firms with high fundamental productivities are initially efficient in utilizing emission-intensive inputs, which induces these firms to be more inclined to use the inputs. However, greater network productivity offsets the rise in emission intensities because firms are able to outsource intermediate goods from other firms at lower prices, which results in the reduction of carbon-intensive input usages. Interestingly, the effects of abatement investments are mixed. We can find the rationale for this from equations (3.24) and (3.25). Equation (3.24) shows that the first-order effect of increasing abatement investment is reducing total emissions. However, equation (3.25) indicates that abatement investments also induce a drop in the price of carbon-intensive inputs and encourages their use by firms. As a consequence, the effect of abatement investments on reducing total emissions can be limited. We call this "the general equilibrium effect" of abatement investments.

We have shown that firm-linkages serve a crucial role in affecting firms' optimal abatement investments and their outsourcing activities under the assumption that the matching probabilities between firms are exogenously given. In the next section, we shift our discussion to study how the structure of production networks is determined—i.e., which firms match with which.

3.4 Endogenous Network Formation

In this section, we study how the matching probability between firms can be specified. As in Lim (2017), we assume that firm linkages are established only by supplier firms which have to bear the random relationship costs ζ. The relationship cost each supplier firm faces is given by $\zeta = \psi\xi$, where ψ refers to the mean relationship cost that is common across all supplier firms, and ξ is the random relationship cost shock which varies between firms. ξ is assumed to be independent and identically distributed across firms with cumulative distribution function F_ξ. The random relationship cost shock, ξ, is additionally assumed to have a unit mean.

To study the endogenous network formation rule, we first express the profits of a supplier χ'-firm attainable from the establishment of a relationship with a particular customer χ-firm:

$$\Pi(\chi, \chi') = \mu^{-\sigma}(\mu - 1)\Delta_H \Delta(\chi)\Phi(\chi'). \tag{3.30}$$

We can verify that the profit of the supplier χ'-firm is fundamentally affected by the production efficiency of the χ'-firm and the size of the customer χ-firm. 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 are able to come up with the following condition which indicates that the upstream χ'-firm establishes a production network with the customer χ-firm when the net profit is positive:

$$\Pi(\chi, \chi') - \psi\xi > 0. \tag{3.31}$$

Thus, the probability that the χ'-firm initiates the relationship with the χ-firm can be specified as

$$m(\chi, \chi') = F_\xi \left[\frac{\Pi(\chi, \chi')}{\psi}\right]. \tag{3.32}$$

As the bilateral profits of the χ' -firm is mainly determined by the network characteristics of input supplying and purchasing firms, the above equation can be expressed in detail as the following.

$$m(\chi, \chi') = F_\xi \left[\frac{\Delta_H \Delta(\chi)\Phi(\chi')}{\bar{\psi}}\right], \tag{3.33}$$

such that $\bar{\psi} = \psi\mu^{\sigma}(\mu - 1)^{-1}$. This result describes the fact that firms with high network productivity (i.e., firms which have formed production networks with cost-efficient upstream firms) have a greater chance to establish downstream trading relationships. It also indicates that firms with high network demand (i.e., firms which have production networks with larger downstream firms) are more likely to establish their own supply networks with upstream producers.

Since the household's demand shifter and the network characteristics are the main drivers that determine the matching probability, we simplify the above matching probability by using a notation

$\widetilde{m}$ as

$$m(\chi, \chi') = \widetilde{m}\left[\Delta_H \Delta(\chi)\Phi(\chi')\right]. \tag{3.34}$$

Using this simplified matching function, we are able to derive the total number of trade customers and suppliers of the χ-firm as the weighted average of matching probabilities between the χ-firm and all of its upstream and downstream trade partners:

$$M_C(\chi) = \int_{S_\chi} \widetilde{m}\left[\Delta_H \Delta(\chi')\Phi(\chi)\right] dG_\chi(\chi'), \tag{3.35}$$

$$M_S(\chi) = \int_{S_\chi} \widetilde{m}\left[\Delta_H \Delta(\chi)\Phi(\chi')\right] dG_\chi(\chi'), \tag{3.36}$$

such that $M_C(\chi)$ and $M_S(\chi)$ respectively denotes the mass of customers and supplier of the χ-firm. Based on these results, we can arrive at the implication that similar firms (in terms of network characteristics) are more likely to be matched, and upon matching they become increasingly similar thanks to the linkages between them. The underlying logic of the inference is straightforward. If efficient supplier firms have a higher chance of establishing production networks with large customer firms, the supplier firms will experience an improvement in their network demand thanks to the linkages with large downstream firms. Likewise, the customer firms also undergo an enhancement of their network productivity as they are able to utilize intermediates produced by efficient upstream firms at lower prices.

From the previous two sections, we have explored the mechanism describing the endogenous formation of inter-firm networks, and its impact on firms' behaviors in determining their optimal abatement investments and outsourcing intermediate outputs via production networks. We now shift gears to explore the effect of freer international trade on the optimal location decision of firms between inland and coastal regions. We are able to investigate the types of firms located in each region under this process, and combined with the previous discussions, we can eventually pin down the channel through which trade liberalization induces the heterogeneous pattern of total emissions and emission intensities across inland and coastal regions through the existence of firm networks.

3.5 Endogenous Export Status and the Geographical Distribution of Firms

In order to simplify our theoretical framework, but maintaining the stylized fact that firms are heterogeneously distributed between inland and coastal regions in many countries, we introduce two regions where firms are able to locate: inland (I) and coastal areas (C). The sets of inland and coastal firms in a home country H are respectively denoted as S_{χ}^{HI} and S_{χ}^{HC}. We additionally assume that domestic trade costs are incurred only for transactions across regions, and these costs are symmetric regardless of the direction of domestic trades: $\tau^{II}(\chi) = \tau^{CC}(\chi) = 1$ and $\tau^{IC}(\chi) = \tau^{CI}(\chi) = \tau_D(\chi)$, where the subscript D represents domestic transactions. The domestic trade frictions take the form of iceberg trade costs, $\tau_D(\chi) > 1$, which implies that more than one unit of intermediate output must be shipped in order for one unit of output to be consumed in the destination. We also introduce an identical foreign country F. Firms in the home country have to pay iceberg international trade costs $\tau_B(\chi) > 1$ to ship their products to foreign trade partners. The subscript B denotes borders between countries.

We start our discussion from an assumption that all firms are *ex ante* distributed in the inland region and make three decisions: first, whether to exit or remain in the market, second, whether to relocate to the coast, and lastly, whether to become an international firm. International trade takes place through ports, which are located in the coastal region in both countries. This setup indicates that the trade costs between home and foreign inland firms are $\tau_{BDD} \equiv \tau_B(\chi) \times \tau_D^2(\chi)$, those between home inland (home coastal) and foreign coastal (foreign inland) firms are $\tau_{BD} \equiv \tau_B(\chi) \times \tau_D(\chi)$, and those between home and foreign coastal firms are $\tau_B(\chi)$. As the foreign country is assumed to be identical to the home country, we can concentrate our focus on firms' location and exporting choice in the home country. The sets of inland and coastal firms in the foreign country will be denoted as S_{χ}^{FI} and S_{χ}^{FC}.

Entry and exit problem of firms

Under these theoretical environment, we consider the firms' entry and exit problem. We follow the standard approach (which has been introduced by Hopenhayn (1992)) that the net profits of firms attainable by entering the market differentiate entering and exiting firms. The total net profit of a χ-firm that enters the market can be calculated by the deduction of its total relationship costs from the variable profits, $\pi^{HI}(\chi; \tau_D(\chi), \tau_B(\chi))$:

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

where $M_C^H(\chi)$ and $M_C^F(\chi)$ respectively refer to the total mass of customer firms of the χ-firm located in home and foreign countries. ψ_1 and ψ_2 are the average relationship costs that the χ-firm in the home country faces by matching with firms at home and abroad. The mean relationship costs between firms across countries are assumed to be greater than those between firms within a country (i.e., $\psi_2 > \psi_1$) because, in general, it is more costly for home firms to search for the best trade partners and finally establish relationships with firms abroad perhaps due to the geographical distance, differences in political regime or information frictions existing across countries. $\psi_1 M_C^H(\chi)$ and $\psi_2 M_C^F(\chi)$ represent the total relationship costs the χ-firm needs to bear. The reason why we only focus on the mass of customers is because we assume that the production network is only built by the supplier firms which have to pay the relationship costs. Extending the discussion from section 3.4, the variable profit and the number of consumers of the χ- firm can be described in detail as[23]

$$\pi^{HI}(\chi; \tau_D(\chi), \tau_B(\chi)) = (\mu - 1)\Delta_H \Delta^{HI}(\chi; \tau_D(\chi), \tau_B(\chi))\Phi^{HI}(\chi; \tau_D(\chi), \tau_B(\chi)), \tag{3.37}$$

and

$$M_C^H(\chi; \tau_D(\chi)) = \int_{S_\chi^{HI}} \widetilde{m} \left[\Delta_H \Delta^{HI}(\chi')\Phi^{HI}(\chi)\right] dG_\chi(\chi') + \int_{S_\chi^{HC}} \widetilde{m} \left[\Delta_H \Delta^{HC}(\chi')\Phi^{HI}(\chi); \tau_D(\chi)\right] dG_\chi(\chi'),$$

$$M_C^F(\chi; \tau_D(\chi), \tau_B(\chi)) = \int_{S_\chi^{FI}} \widetilde{m} \left[\Delta_H \Delta^{FI}(\chi')\Phi^{HI}(\chi); \tau_{BDD}(\chi)\right] dG_\chi(\chi') + \int_{S_\chi^{FC}} \widetilde{m} \left[\Delta_H \Delta^{FC}(\chi')\Phi^{HI}(\chi); \tau_{BD}(\chi)\right] dG_\chi(\chi').$$

$\Delta^{HI}(\chi; \tau_D(\chi), \tau_B(\chi))$ and $\Phi^{HI}(\chi; \tau_D(\chi), \tau_B(\chi))$ are the network characteristics of an inland χ-firm in the home country, and both of them are affected by domestic and international trade costs. Both $\tau_D(\chi)$ and $\tau_B(\chi)$ reduce the matching probability since these are additional costs that firms need to bear to establish networks. Based on this setup, the cutoff determining which firms exit the market and which firms remain is determined by

$$\Pi^{\text{enter}}(\chi; \tau_D(\chi), \tau_B(\chi)) = 0. \tag{3.38}$$

[23]See the appendix for detailed form of $\Delta^{HI}(\chi; \tau_D(\chi), \tau_B(\chi))$ and $\Phi^{HI}(\chi; \tau_D(\chi), \tau_B(\chi))$.

Equation (3.38) gives us the pairing of fundamental efficiency (ϕ) and demand (δ) of the marginal firms which are indifferent between staying and exiting the market.

Export status of firms

After firms choose to remain in the market, they determine their location and export (import) statuses; firms who establish networks with foreign firms both export and import intermediate goods. To make our framework consistent and straightforward, we focus on the likelihood of firms relocating to the coast and being matched with foreign trade partners. We follow the framework introduced in section 3.4 to derive the probability of the home country firms establishing relationships with foreign firms. As illustrated in equation (3.33), the probability of the χ-firm to establish networks with foreign χ'-trade partners is positively correlated with the (expected) profits of the supplier firm, which in turn implies that greater network efficiency (demand) of the χ-firm and larger network demand (efficiency) of the foreign customer raise the likelihood of matching:

$$m_C^F(\chi', \chi; \tau_B(\chi), \tau_D(\chi)) = F_\xi\left[\frac{\Delta_H \Delta(\chi')\Phi(\chi)}{\bar{\psi_2}}; \tau_B(\chi), \tau_D(\chi)\right],$$
$$m_S^F(\chi, \chi'; \tau_B(\chi), \tau_D(\chi)) = F_\xi\left[\frac{\Delta_H \Delta(\chi)\Phi(\chi')}{\bar{\psi_2}}; \tau_B(\chi), \tau_D(\chi)\right],$$

such that $\bar{\psi_2} = \psi_2 \mu^\sigma (\mu - 1)^{-1} \alpha^{1-\sigma}$, $\chi \in S_\chi^{HI},\ S_\chi^{HC}$and $\chi' \in S_\chi^{FI},\ S_\chi^{FC}$. $m_C(\chi', \chi)$ and $m_S(\chi, \chi')$ are respectively the bilateral matching probabilities that the χ-firm is matched with a foreign customer and supplier firm. Therefore, we can illustrate the total mass of international and domestic firms as the weighted average of the matching probabilities as shown in equations (3.35) and (3.36) by considering the possible location of the χ-firm:

$$M_C^F(\chi; \tau_D(\chi), \tau_B(\chi)) = \int_{S_\chi^{FI} \cup S_\chi^{FC}} m_C^F(\chi', \chi; \tau_B(\chi), \tau_D(\chi)) dG_\chi(\chi'),$$
$$M_S^F(\chi; \tau_D(\chi), \tau_B(\chi)) = \int_{S_\chi^{FI} \cup S_\chi^{FC}} m_S^F(\chi, \chi'; \tau_B(\chi), \tau_D(\chi)) dG_\chi(\chi').$$

The openness of a χ-firm, $i(\chi; \tau_D(\chi), \tau_B(\chi)$, is defined as the total number of foreign trade partners:

$$i(\chi; \tau_D(\chi), \tau_B(\chi)) \equiv M_C^F(\chi; \tau_D(\chi), \tau_B(\chi)) + M_S^F(\chi; \tau_D(\chi), \tau_B(\chi)). \tag{3.39}$$

Thus, using the complementary probability, the likelihood of firms to remain as domestics, $\hat{i}(\chi;\tau_D(\chi),\tau_B(\chi))$, is

$$\hat{i}(\chi;\tau_D(\chi),\tau_B(\chi)) = 1 - i(\chi;\tau_D(\chi),\tau_B(\chi)). \tag{3.40}$$

The relocation problem of firms

Next, we shift gears to explore the location decision of firms. We assume that firms face a random relocation cost shock ρ from a cumulative density function H_ρ.[24] 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. The implication of such setup was that larger and efficient firms are more likely to be matched with other firms. The assumption of a random relocation cost serves a similar role in the sense that large firms are more likely to relocate towards the coast due to greater expected profits (compared to that of smaller firms) arising from shifting their locations to the coast. In other words, firms choose to relocate towards the coast if

$$\Pi^{HC}(\chi;\tau_D(\chi),\tau_B(\chi)) - \varphi\rho > 0, \tag{3.41}$$

where $\Pi^C(\chi)$ is the expected total profit of the χ-firm by locating on the coast, and φ is the mean relocation costs that is common across firms. In detail,

$$\Pi^{HC}(\chi;\tau_D(\chi),\tau_B(\chi)) = \pi^{HC}(\chi;\tau_D(\chi),\tau_B(\chi)) - \psi_1 M_C^H(\chi;\tau_D(\chi)) - \psi_2 M_C^F(\chi;\tau_D(\chi),\tau_B(\chi)),$$

where the variable profit of a firm locating on the coast is[25]

$$\pi^{HC}(\chi;\tau_D(\chi),\tau_B(\chi)) = (\mu-1)\Delta_H\Delta^{HC}(\chi;\tau_D(\chi),\tau_B(\chi))\Phi^{HC}(\chi;\tau_D(\chi),\tau_B(\chi)). \tag{3.42}$$

The total mass of customer firms in home and foreign countries are

$$M_C^H(\chi;\tau_D(\chi)) = \int_{S_\chi^{HC}} \widetilde{m}\left[\Delta_H\Delta^{HC}(\chi')\Phi^{HC}(\chi)\right] dG_\chi(\chi') + \int_{S_\chi^{HI}} \widetilde{m}\left[\Delta_H\Delta^{HI}(\chi')\Phi^{HC}(\chi);\tau_D(\chi)\right] dG_\chi(\chi'),$$
$$M_C^F(\chi;\tau_D(\chi),\tau_B(\chi)) = \int_{S_\chi^{FC}} \widetilde{m}\left[\Delta_H\Delta^{FC}(\chi')\Phi^{HC}(\chi);\tau_B(\chi)\right] dG_\chi(\chi') + \int_{S_\chi^{FI}} \widetilde{m}\left[\Delta_H\Delta^{FI}(\chi')\Phi^{HC}(\chi);\tau_B(\chi),\tau_D(\chi)\right] dG_\chi(\chi').$$

[24] We can simply think of this relocation cost shock as a taste parameter on currently being located in the inland region. Firms compare the exogenously given taste parameter to the expected benefit they would be able to obtain from relocation towards the coast.

[25] See the appendix for detailed form of $\Delta^{HC}(\chi;\tau_D(\chi),\tau_B(\chi))$ and $\Phi^{HC}(\chi;\tau_D(\chi),\tau_B(\chi))$.

Therefore, the probability of relocation, $r(\chi;\tau_D(\chi),\tau_B(\chi))$, can be simply illustrated as

$$r(\chi;\tau_D(\chi),\tau_B(\chi)) = H_\rho\left[\frac{\Pi^{HC}(\chi;\tau_B(\chi),\tau_D(\chi))}{\varphi}\right], \tag{3.43}$$

and the likelihood of a firm remaining in the inland region, $\hat{r}(\chi;\tau_D(\chi),\tau_B(\chi))$, is the complementary probability of relocation to the coast:

$$\hat{r}(\chi;\tau_D(\chi),\tau_B(\chi)) = 1 - r(\chi;\tau_D(\chi),\tau_B(\chi)). \tag{3.44}$$

Classification of firms by types

Based on the results we have derived thus far in this section, we are able to pin down the total mass of firms based on their locations and export statuses by the multiplication of the probabilities of entry/exit, relocation, and matching with foreign firms: the superscripts in the following equations refer to inland domestics (ID), coastal domestics (CD), inland internationals (II), and coastal internationals (CI).

$$M^{ID} = \int_{S_\chi} \underbrace{p\left(\Pi^{\text{enter}}(\chi) > 0\right)}_{\text{Prob of entry}} \times \underbrace{\hat{i}(\chi;\tau_D(\chi),\tau_B(\chi))}_{\text{Prob to be a domestic firm}} \times \underbrace{\hat{r}(\chi;\tau_D(\chi),\tau_B(\chi))}_{\text{Prob to be an inland firm}} \, dG_\chi(\chi), \tag{3.45}$$

$$M^{CD} = \int_{S_\chi} \underbrace{p\left(\Pi^{\text{enter}}(\chi) > 0\right)}_{\text{Prob of entery}} \times \underbrace{\hat{i}(\chi;\tau_D(\chi),\tau_B(\chi))}_{\text{Prob to be a domestic firm}} \times \underbrace{r(\chi;\tau_D(\chi),\tau_B(\chi))}_{\text{Prob to be a coastal firm}} \, dG_\chi(\chi), \tag{3.46}$$

$$M^{II} = \int_{S_\chi} \underbrace{p\left(\Pi^{\text{enter}}(\chi) > 0\right)}_{\text{Prob of entery}} \times \underbrace{i(\chi;\tau_D(\chi),\tau_B(\chi))}_{\text{Prob to be an international firm}} \times \underbrace{\hat{r}(\chi;\tau_D(\chi),\tau_B(\chi))}_{\text{Prob to be an inland firm}} \, dG_\chi(\chi), \tag{3.47}$$

$$M^{CI} = \int_{S_\chi} \underbrace{p\left(\Pi^{\text{enter}}(\chi) > 0\right)}_{\text{Prob of entery}} \times \underbrace{i(\chi;\tau_D(\chi),\tau_B(\chi))}_{\text{Prob to be an international firm}} \times \underbrace{r(\chi;\tau_D(\chi),\tau_B(\chi))}_{\text{Prob to be a coastal firm}} \, dG_\chi(\chi). \tag{3.48}$$

3.6 Networks and Regional Environmental Quality

From the previous two sections, we have discussed 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 under firm linkages. Based on the framework provided, we are able to measure the effect of networks on the regional environmental quality in terms of total emissions and emission intensities.

The total pollution emitted in inland and coastal regions (E^I and E^C, respectively) are the total weighted averages of emissions by inland and coastal firms, which can be calculated as follows:

$$E^I = \int_{S_\chi} \underbrace{p\left(\Pi^{\text{enter}}(\chi) > 0\right) \times \hat{r}(\chi) \times e(\chi)}_{\text{Total emissions by an inland firm}} dG_\chi(\chi),$$

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

Likewise, the regional emission intensities (EI^I and EI^C, respectively) can be derived as the ratio of total emissions to the level of output productions both of which describe the pollution emissions per unit of output respectively in inland and coastal regions:

$$EI^I = \frac{\int_{S_\chi} p\left(\Pi^{\text{enter}}(\chi) > 0\right) \times \hat{r}(\chi) \times e(\chi) dG_\chi(\chi)}{\int_{S_\chi} \underbrace{p\left(\Pi^{\text{enter}}(\chi) > 0\right) \times \hat{r}(\chi) \times X(\chi)}_{\text{Total output by an inland firm}} dG_\chi(\chi)},$$

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

The theoretical framework described throughout this paper enable us to study the interplay of international trade cost reductions and firm linkages in influencing the regional environmental quality via the channels of firms' network characteristics.

In the following section, we perform numerical exercises to quantifiably describe the effect of networks on the regional environment based on the theoretical framework discussed throughout this paper.

4 Numerical Exercise

4.1 Parametric Assumptions

As much of our theoretical model is built on Lim (2017), we follow the same parametric assumptions on the distribution of fundamental characteristics, G_χ: the fundamental efficiency and demand of a firm, ϕ and δ, are jointly log-normally distributed with mean zero and variance equal to one. The random draws of these fundamentals are also assumed to be independent. We additionally adopt Lim's assumption on the distribution of the relationship cost shock, F_ξ, as corresponding to a Weibull distribution since this distribution yields an economic interpretation as the minimum cost among a series of cost draws within a given relationship (see Lim (2017) for more detail). As an extension, we study the location decision of firms by introducing a random relocation cost shock which follows H_ρ. In order to capture the fact that large and efficient firms are comparatively better able to bear the relocation costs, and therefore more likely to relocate to the location where they can reduce costs and maximize profits, we assume that H_ρ also follows a Weibull distribution. This implies that the relocation cost of a firm drawn from H_ρ is the minimum moving cost among a series of cost draws.

4.2 Parameter Values

Based on these parametric assumptions, the theoretical model discussed in section 3 is built on the following parameters:

Parameter	Notation
mean domestic relationship cost	ψ_1
shape of relationship cost distribution	s_ξ
elasticity of substitution	σ
domestic trade cost	τ_D
supply of emission-intensive input	D
average relocation cost	φ
mean foreign relationship cost	ψ_2
price of emission-intensive input	ω
tax rate	t
carbon conversion parameter	ϵ

Table 1: Parameters

We take values for the first four parameters directly from Lim (2017), who calibrated these parameters based on business data from Capital IQ and Compustat. The domestic trade cost is calculated from Lim (2016) which gives the overall level of trade costs (0.688) and the elasticity of trade cost with respect to distance between firms (0.348). As Lim's paper assumes that the functional form of domestic trade frictions is $\tau_D = (1 + 0.688 \times distance)^{0.348}$, we obtain the value 1.17 from Lim's assumption that firms are separated from each other with a maximum distance of one (on a unit circle). We normalized the total supply of labor and the supply of emission-intensive input to one. The average relocation cost of firms is chosen such that the share of coastal firms in the model mirrors that of the real-world U.S.—around 80%, based on data from Statistics of U.S. Businesses (2013). The mean foreign relationship cost is proxied by information frictions (matching efficiency) between Japanese firms studied in Sato (2009).

On top of these parameter values required to define the characteristics of firm-to-firm production networks, we additionally choose the price of the emission-intensive production factor as a numeraire, and calculate the tax rate in proportion to the numeraire. Among a variety of energy sources that firms are able to utilize, we particularly focus on natural gas (versus coal, petroleum or some other carbon-intensive energy source) because, according to the Energy Information Administration (EIA), the share of natural gas as the primary energy source of the U.S. manufacturing sector increased consistently from 1950 to 2016 (from 26% to 50% – Monthly Energy Review, September 2017), and natural gas is comparatively more homogeneous than coal and petroleum with respect to its type.[26] The EIA also provides information about the carbon conversion rate of natural gas, which is 0.1171 pounds of CO_2 per cubic foot of gas burned.[27] The carbon tax per ton of CO_2 varies in the literature; however, the summary report from Tol and Yohe (2006) about the social cost of carbon (SCC) suggests \$12 per ton of CO_2 as the estimate of SCC in 2005. We obtain \$0.0007026 as the emission tax per cubic foot of natural gas.[28] As the price of natural gas per cubic foot in 2017 was \$0.0145,[29] we are able to calculate the tax rate as \$0.048 when the price of natural gas is normalized to one. The following table summarizes the parameter values used for numerical analyses.

[26] See https://www.eia.gov/energyexplained/index.php?page=us_energy_industry.
[27] See https://www.eia.gov/environment/emissions/co2_vol_mass.php.
[28] The calculated emission tax is expressed in 2005 (current) dollars.
[29] See https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm.

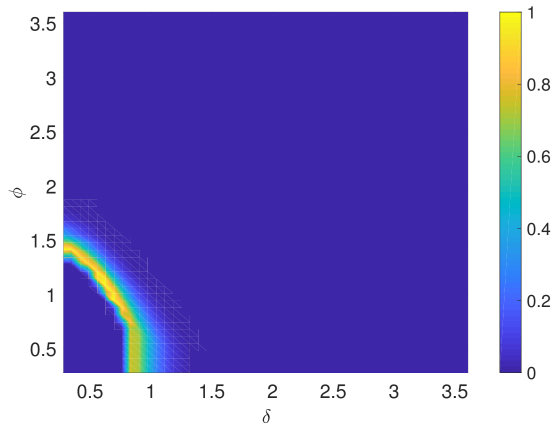
Parameter	Notation	Value	Note
mean domestic relationship cost	ψ_1	0.216	Lim (2017)
shape of relationship cost distribution	s_ξ	0.9565	
elasticity of substitution	σ	4	
domestic trade cost	τ_D	1.17	Lim (2016)
supply of emission-intensive input	D	1	Normalized to one
average relocation cost	φ	0.02	Chosen so as to have a share of coastal firms equal to 80%
mean foreign relationship cost	ψ_2	0.6	Sato (2009)
price of emission-intensive input	ω	1	Numeraire
tax rate	t	0.048	Tax rate takes 5% of the price of 1 cubic foot of natural gas
carbon conversion parameter	ϵ	0.1171	1 cubic foot of natural gas generates 0.1171 lb of CO_2

Table 2: Parameter choice

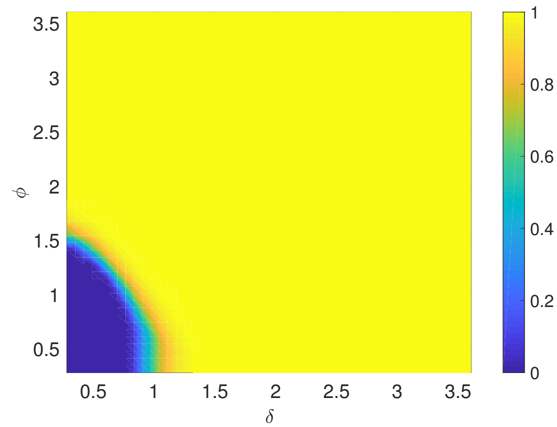
4.3 Abatement Investments, Outsourcing Activities and the Regional Environmental Quality

4.3.1 (ϕ, δ)-Mesh Grid and the Types of Firms

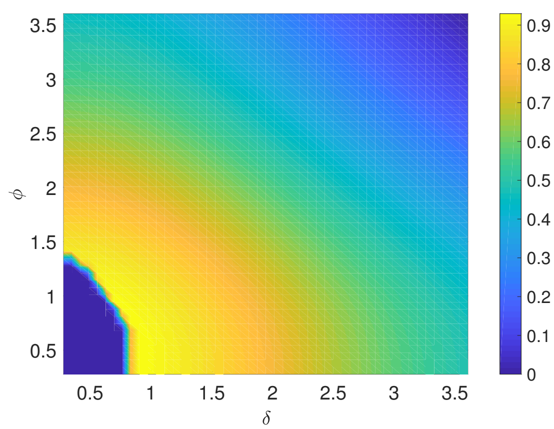
As the main theme of this paper is to provide a plausible channel through which geographical differences in total emissions and emission intensities arise, we study how firms differ in their behavior with regard to investing on abatement and in outsourcing and how these decisions depend upon their locations. We abstract from heterogeneous industrial composition, environmental regulations and technological differences across regions in order to limit our focus on the role of inter-firm trade in intermediate goods via production networks. Before we dive into our main discussion, we plot the likelihood of firms to locate either in inland or in coastal regions and to be matched with foreign trade partners by their fundamental characteristics under the assumption that international trade is perfectly liberalized. The following figures will help us understand firms' behaviors in both regions and relate those to regional environmental quality, topics which will be discussed later.



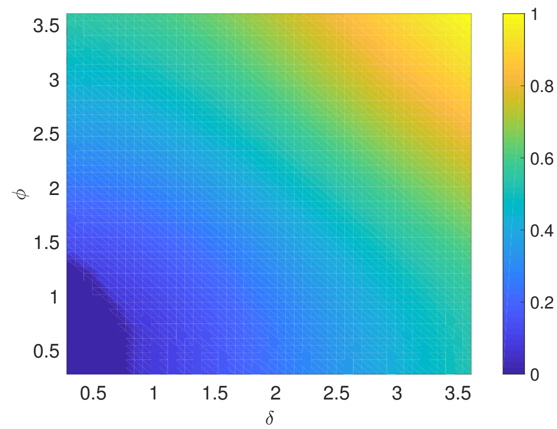
(a) Probability of being an inland firm



(b) Probability of being a coastal firm



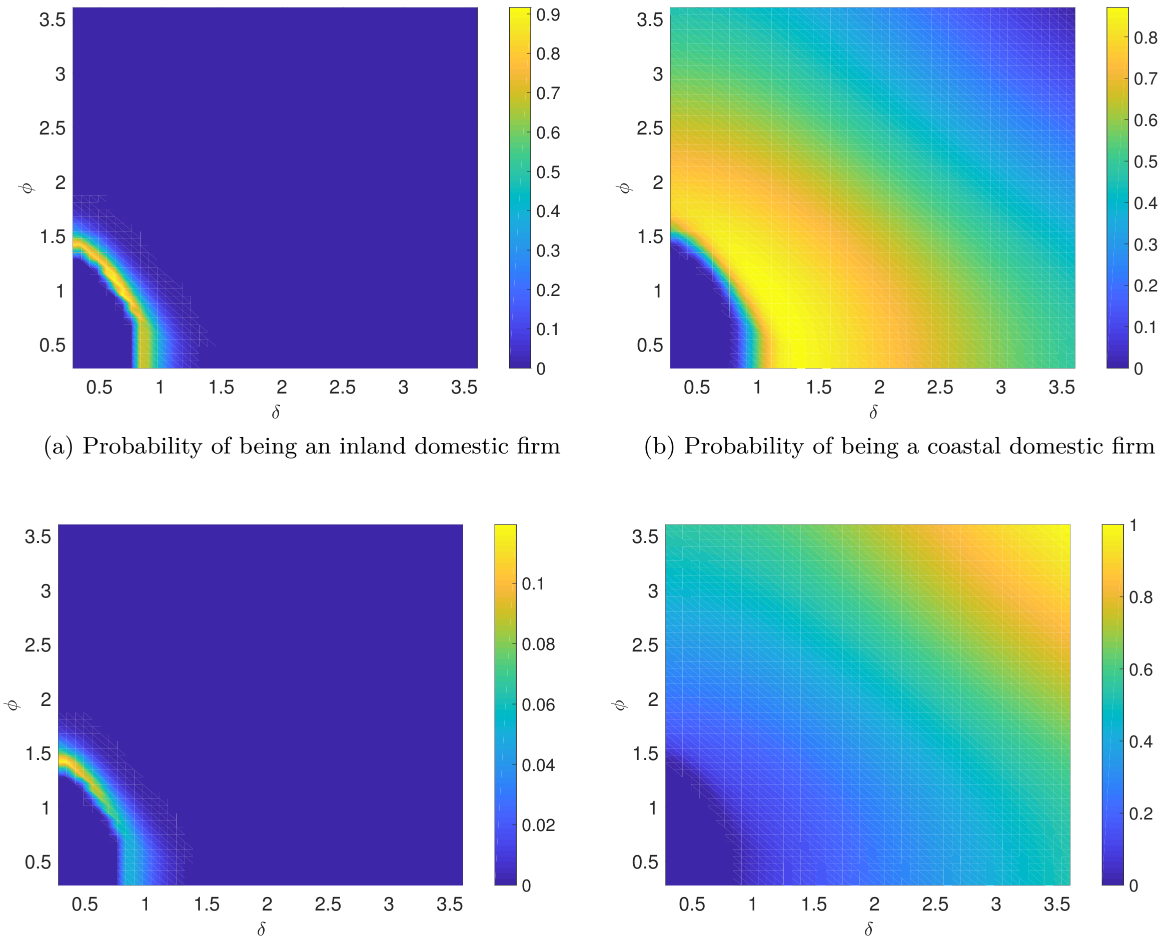
(c) Probability of being a domestic firm



(d) Probability of being an international firm

Figure 6: Location and export status by firms' fundamental characteristics

What we can see first in Figure 6 is that the smallest and least productive firms (firms who have drawn low values of ϕ and δ from the distribution of fundamental characteristics) exit the market, which is the reason why the lower left corners of the Figures are consistently the darkest blue (indicating probability zero). Figures 6a and 6b tell us that relatively less efficient (i.e., low values of fundamental productivity around 1.5) and smaller (i.e., low values of fundamental demand around 1) firms tend to locate in inland regions whereas comparatively productive and larger firms are increasingly likely to position in the coastal regions. Figures 6c and 6d further indicates that more productive and larger firms are more likely to establish production relationships with foreign firms (compared to smaller and less efficient firms) due to their greater expected profits even in the presence of international trade frictions.



(a) Probability of being an inland domestic firm

(b) Probability of being a coastal domestic firm

(c) Probability to be inland international firm

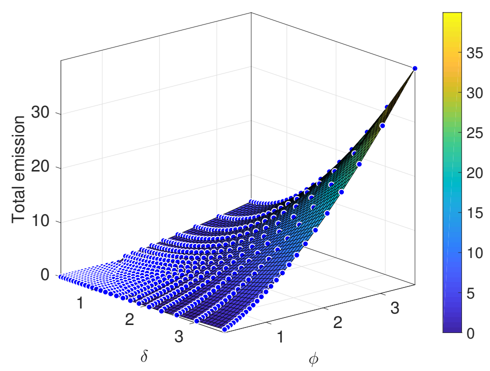
(d) Probability of being a coastal international firm

Figure 7: Firm types by their fundamental characteristics

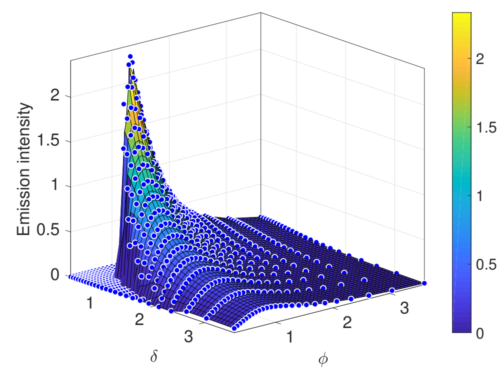
There are variations between firms within a region. Comparing figures 7a and 7c, we notice that firms with higher fundamental productivity are more likely to be international firms compared to those with lower efficiency but facing higher fundamental demands. This is because the fundamental productivity indicates how efficiently firms use carbon-intensive production inputs, which directly affects firms' profitability, while the fundamental demand indirectly influences the profitability of firms via demands arising from networks. Likewise, Figures 7b and 7d tell us the probability to relocate towards the coast, and at the same time, to become international firms, is increasing as firms become more productive and face greater demand for their products.

4.3.2 Total Emissions and Emission Intensities of Firms

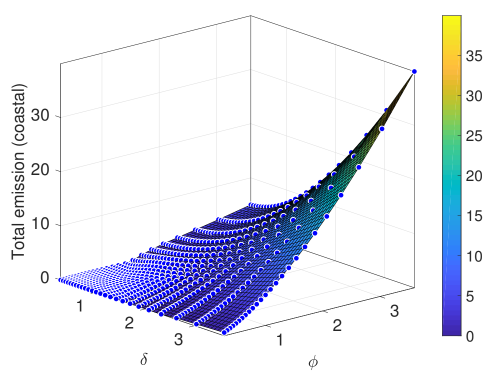
Taking the location and export/import statuses of firms by their fundamental characteristics into account, we derive the total emissions and emission intensities of firms. We first pay attention to the total emissions produced by firms.



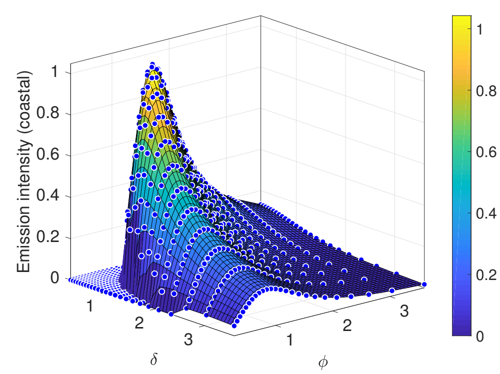
(a) Emissions by all firms



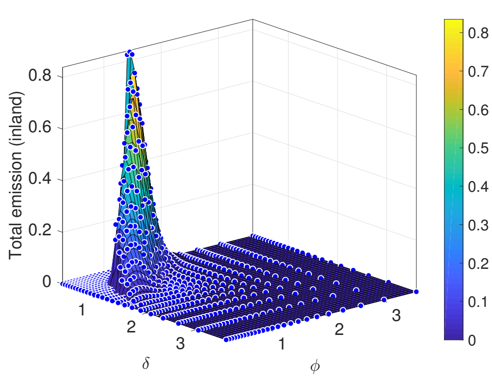
(b) Emission intensities of all firms



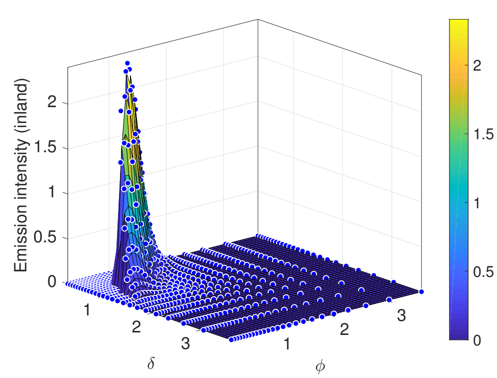
(c) Emissions (coastal firms)



(d) Emission intensities (coastal firms)



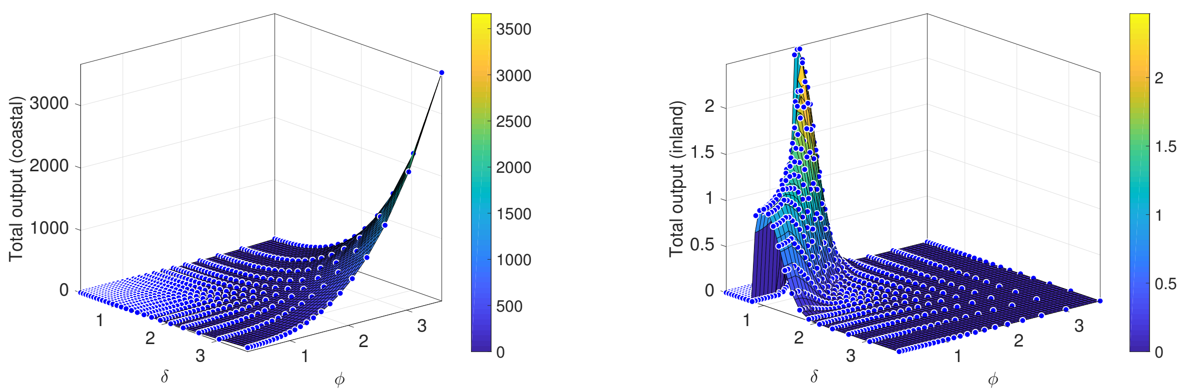
(e) Emissions (inland firms)



(f) Emission intensities (inland firms)

Figure 8: Total emissions and emission intensities by firm types

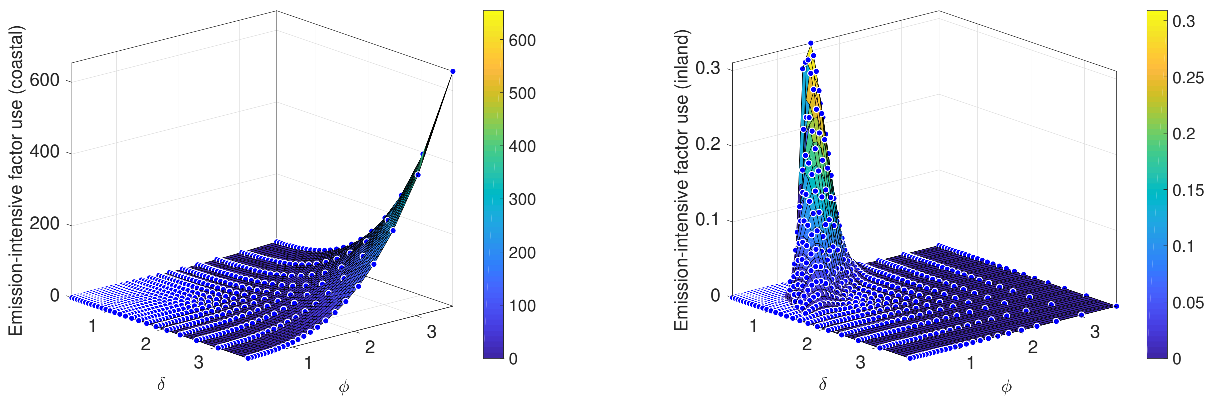
Figure 8a shows that firms with great ϕ and δ emit more pollution since firms with better fundamentals are larger, and therefore have higher demands for carbon-intensive inputs due to the scale effect. From the figural similarity between Figures 8c and 8a and the position of coastal firms in the (ϕ, δ)-grid illustrated in Figure 6b, we can see that most of the emissions in the economy are emitted in the coastal region both due to greater scale of productions by coastal firms and their geographical concentration within the coastal region. Similar to Figure 8a, Figure 8e illustrates that inland firms with greater fundamental productivity emit relatively more pollution compared to firms with lower efficiency. We can additionally verify that inland firms generate absolutely less amount of pollution compared to coastal firms due to smaller scale of production. Figure 9 verifies the plausibility of this conjecture from the figural similarity between Figures 9a and 8c; and Figures 9b and 8e: the greater the level of output, the more pollution is generated.



(a) Output production (coastal firms) (b) Output production (inland firms)

Figure 9: Output productions of inland and coastal firms

The reason why greater output generates more pollution is clear. As shown in the following figure, the enlarged scale of output indicates that firms utilize production factors in a greater amount, including carbon-intensive inputs. We can verify from Figure 10 that the carbon-intensive factors used by firms are the fundamental link between total emissions and output production activities by firms.

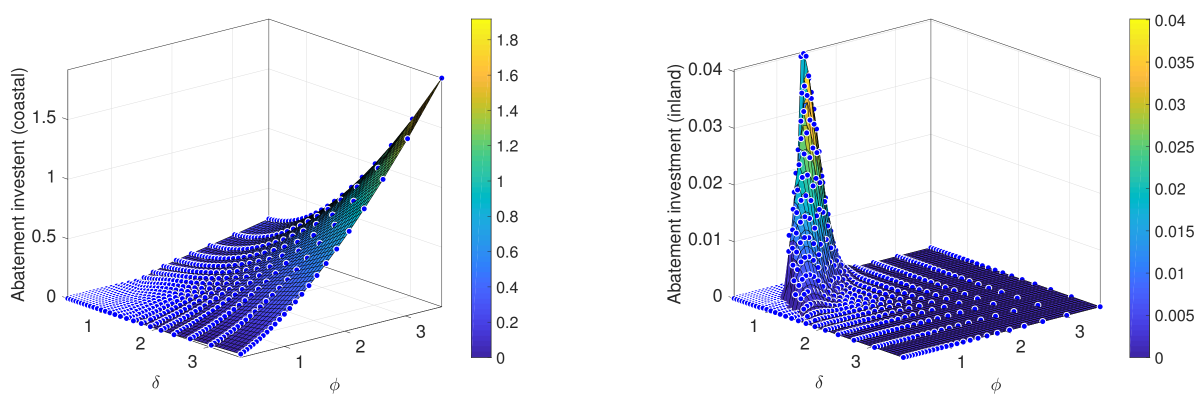


(a) Carbon-intensive factor use (coastal firms)

(b) Carbon-intensive factor use (inland firms)

Figure 10: Carbon-intensive input usage by firm type

However, there still remains the question of why greater output necessarily leads to more pollution emissions — the fact that firms are able to produce large amount of outputs (and thus use more carbon-intensive factors) implies that firms are also profitable enough to enlarge their investments in abatement as shown in Figure 11.



(a) Abatement investment (coastal firms)

(b) Abatement investment (inland firms)

Figure 11: Abatement investments by firm location

The counteracting forces of production factor usage and abatement investments transform our question in the following way: What makes it the case that the greater scale of production activities outweighs the effect of abatement investments and results in an overall increase in total emissions? We find the answer from equation (3.25) which tells us that the price of the carbon-intensive factor is an inverse measure of abatement investments. The first order effect of larger abatement investments is a reduction in pollution, as abatement decreases emissions from use of the carbon-intensive input. But a second order effect also results from the decrease in the effective price of the carbon-intensive input (arising from abatement reducing payments towards the emissions tax); a lower input price incentivizes more use of the dirty input. The effect of abatement investments on the use of the carbon-intensive factor is clearly shown in Figure 12 that an expansion in abatement investments exponentially increases the quantity demanded of carbon-intensive inputs.

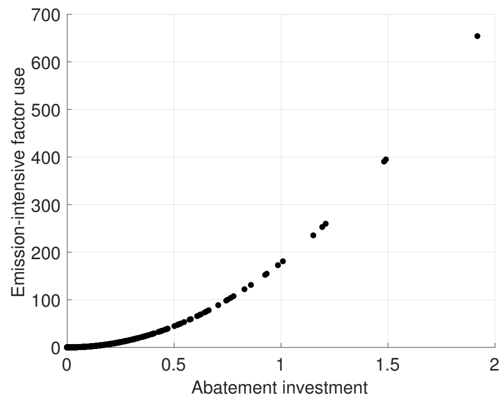


Figure 12: Relationship between abatement and carbon-intensive factor use

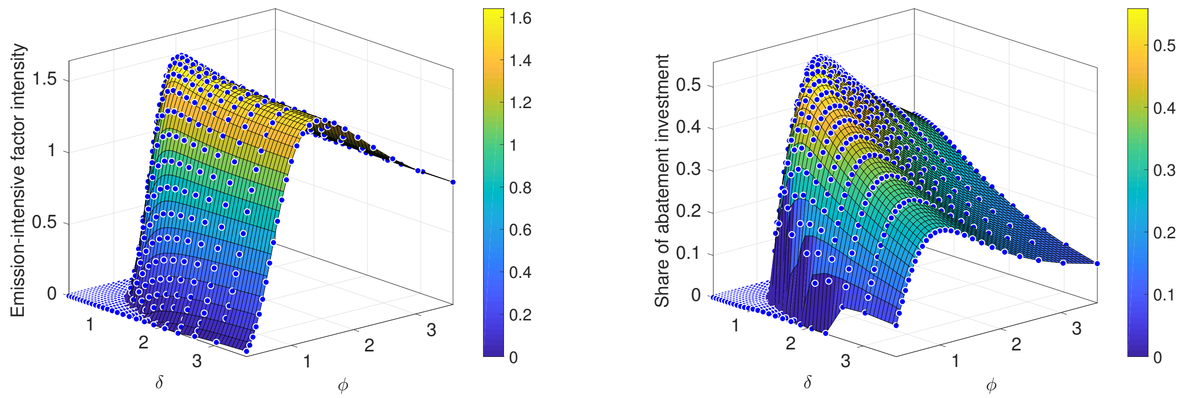
To summarize the discussion thus far, total emissions are fundamentally determined by the scale of output, which is positively correlated with the carbon-intensive factor usage: *the scale effect*. The greater profitability of larger, more productive firms allows them to increase their investments on abatement to reduce emissions and emission tax payments. However, firms are also increasingly able to expand their consumption of carbon-intensive inputs as they increase the expenditure on abatement: *the general equilibrium effect.* Thus, the scale and general equilibrium effects dampen the first-order effect of abatement investments on reducing total emissions. All in all, we are able to conclude that the coastal regions experience greater total emissions compared to inland regions because of (a) the number of firms located on the coast, and (b) the greater scale of production activities (ironically supported by abatement investments) which induce greater usage of carbon-intensive factors by coastal firms.

Next, we shift gears to discuss emissions intensities of firms. Figure 8b shows that inland firms tend to have the greatest emission intensities compared to coastal firms: the yellow peak of the surface describes the emission intensities of the largest and most efficient inland firms (i.e., inland international firms). We analyze this phenomenon based on the channels through which the emission intensities of firms are affected. Recall that emission intensities are measured by the ratio of total emissions to the output level. Therefore, the most apparent channel that determines firms' emission intensities is the level of output: a higher level of output induces lower emission intensities, all else equal. The second channel — which is the main focus of this paper — is the scale of total emissions. As illustrated in equation (3.24), total emissions of firms are affected by two determinants: (a) the amount of carbon-intensive inputs used ($d(\chi)$), and (b) the scale of abatement investments ($f_A(\chi)$). As discussed previously, increasing abatement investment has the first-order effect of reducing the total amount of pollution. However, it causes the general equilibrium effect of raising firms' demand for carbon-intensive inputs by lowering its effective price, arising from the reduction in emission tax payments. Due to these counteracting forces, the effect of abatement investments on reducing total emissions can be limited.[30] In contrast to firms' abatement investments, firm-linkages enable firms to outsource intermediate goods which can replace carbon-intensive inputs (these two types of production factors were assumed to be gross substitutes in Section 3). This means that firms' outsourcing activities are more effective in reducing emissions than abatement investments. With the ability to substitute the inputs used in production, firms are able to reduce their total emissions for a given level of output. Figures 8d and 8f can be interpreted in this manner.

We first study the emission intensities of coastal firms. The clear pattern we observe from Figure 8d is that the most productive and largest coastal firms (i.e., firms with the largest ϕ and δ) exhibit significantly lower emission intensities compared to smaller and less efficient firms. As discussed, this pattern can be attributed to the greater level of output by large firms. However, we should recall that total emissions also increase as a result of production activities. Then, what leads to increases in total emissions being outpaced by increases in the level of production? On the one hand, larger abatement investments conducted by the large and efficient firms serve an important role in reducing the total size of emissions. On the other hand, these firms offset the general equilibrium effect arising from abatement investments by sourcing intermediate inputs via networks, which further lowers pollution emissions. In order to demonstrate this rationale, we study the factor intensity of coastal firms and the share of abatement investments in total expenditures

[30] The net effect would be determined by the carbon conversion parameter (ϵ), and most importantly, by firms' price elasticity of demand for carbon-intensive inputs.

on reducing emissions: the total expenditure is the sum of abatement investments and the costs of purchasing intermediate goods from upstream supplier firms.



(a) Carbon-intensive factor intensity

(b) Share of abatement investments in total expenditure on emission reduction

Figure 13: Factor intensity and the share of abatement investments of coastal firms

Figure 13 describes firms' behaviors of replacing carbon-intensive inputs with intermediate inputs, and the reduction in the share of abatement investments in total expenditures as related to firms' fundamental sizes and productivities. First, Figure 13a illustrates the intensity of firms in utilizing carbon-intensive inputs compared to outsourced intermediate goods. The inverse U-shaped surface indicates that firms increase the relative usage of carbon-intensive production factors as they become more efficient in using these inputs and are able to invest more on abatement; however, as firms become even larger and more productive, the relative use of intermediate goods begins to increase. We are able to explain this pattern from the factor prices that firms face.

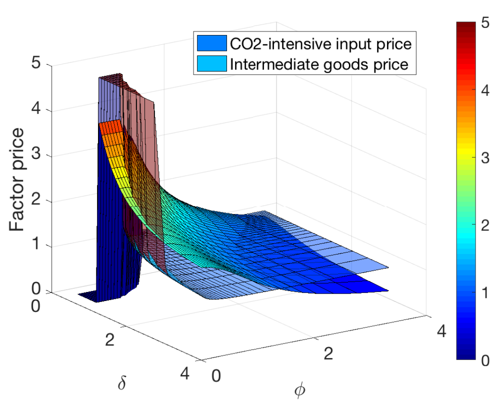


Figure 14: Factor prices by firms

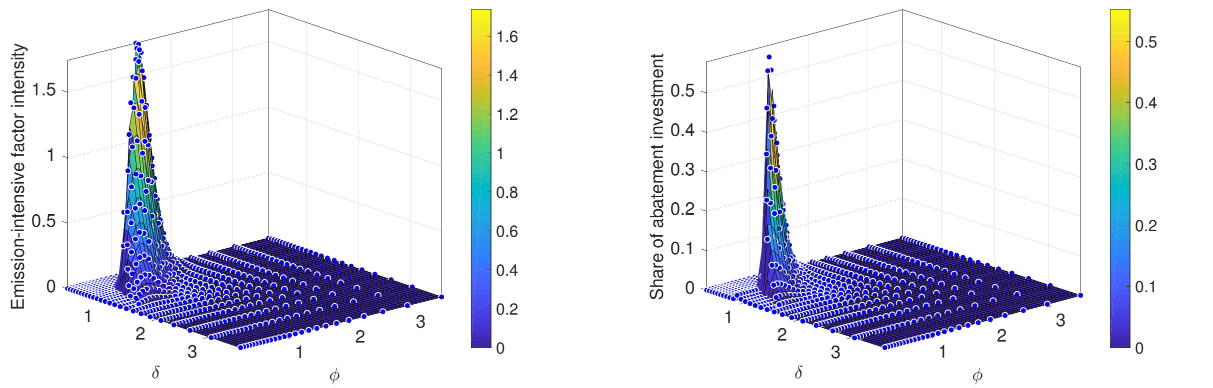
Figure 14 shows two overlapping surfaces. The L-shaped surface describes the unit price of the carbon-intensive input, while the colored surface passing through the bottom of the L-shaped surface illustrates the mean price of intermediate inputs faced by firms. What we can learn from the Figure is that factor prices vary according to the fundamental characteristics of firms. Specifically, firms are able to dramatically lower the effective price of carbon-intensive inputs because of increased abatement investments as they become larger and more efficient. We can also observe that the price of intermediate goods decreases as firms grow larger and more productive. This is because a customer firm with more robust connections to efficient upstream firms enables the firm to obtain intermediate goods at a lower price.[31][32]

From the relative position of the two surfaces, we can understand the inverse U-shaped surface in Figure 13a. The medium-sized coastal firms — such as those who have drawn large δ (fundamental demand, or the taste parameter on the product) but small ϕ (fundamental productivity), and vice versa — increase their abatement investments and enjoy a lower relative price for carbon-intensive inputs: the L-shaped surface is located below the downward sloping surface indicating the price of intermediate inputs. Due to the general equilibrium effect, these firms are able to increase their consumption of carbon-intensive inputs. The most productive and large firms, on the other hand, can reduce their relative demand for carbon-intensive inputs because of their upstream networks, which lowers the relative price of intermediate inputs. Therefore, these firms can utilize intermediate inputs more intensively than carbon-intensive factors.

The outsourcing activities of high-end coastal firms can also be verified in Figure 13b. It depicts that the high-end coastal firms reduce their share of abatement investments but instead focus more of their expenditures on reducing total emissions by outsourcing intermediate goods: for such firms, the share of abatement investment is only around 10% of the total expenditures on emission reductions. Smaller coastal firms, however, increase their expenditure share of abatement investments because of the limited scope of their networks, and ensuing inability to effectively source

[31] Equations (3.11), (3.13) and (3.15) imply that the mean price of intermediate goods faced by each firm is determined by the customer firm's network productivity (i.e., the composite of trade partners' network efficiencies), which is also affected by the fundamental efficiency.

[32] It is also possible to see that the price of intermediate goods become lower for firms with greater fundamental demand at a given fundamental efficiency. Even though the network demand, which is intrinsically affected by the fundamental demand (taste parameter), does not directly affect the price of intermediate inputs, greater network demand of a firm improves the network productivity by raising the probability of matching with efficient firms in the network. Therefore, firms with higher fundamental taste parameter face a relatively lower price of intermediate inputs compared to firms with a lower fundamental taste parameter.



(a) Carbon-intensive factor intensity

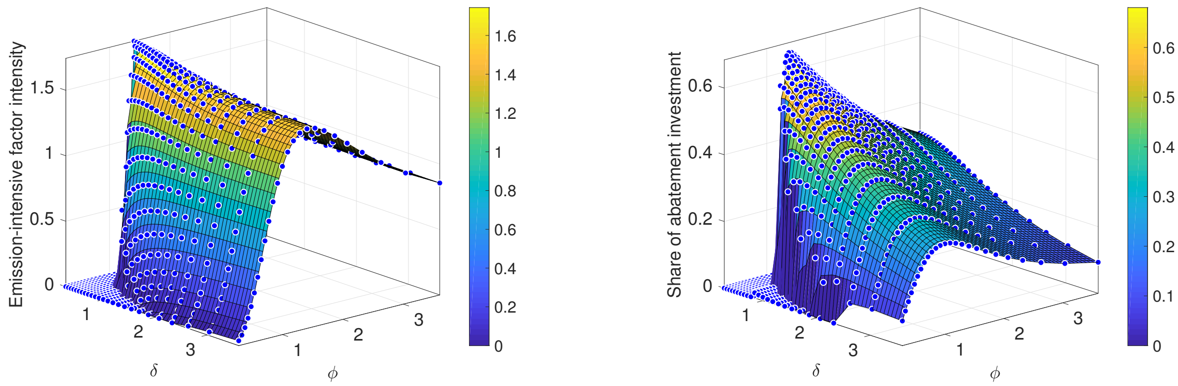
(b) Share of abatement investments from total expenditure to reduce emissions

Figure 15: Factor intensity and the share of abatement investments of inland firms

intermediate inputs from efficient suppliers.

All in all, we can conclude that the high-end coastal firms are characterized by lower emission intensities compared to smaller and less productive medium-sized firms due to their (a) greater scale of production, (b) enlarged abatement investments, and most importantly, (c) intensified outsourcing activities which outweigh abatement investments. Abatement investments are the most attractive channel through which smaller and less productive firms can minimize input costs, but as a consequence, greater emission intensities are induced due to the general equilibrium effect of abatement investments.

We now turn our focus towards inland firms. Keeping the location of firms on the (ϕ, δ) grid in mind, it is possible to ask the question: "Why do efficient inland firms exhibit greater emission intensities compared to smaller and less productive inland firms as shown in Figure 8f?" The reason why smaller and less efficient inland firms are able to exhibit lower emission intensities compared to large firms is that those firms are not productive enough to bear abatement costs and thus face an extremely high price of carbon-intensive inputs. This causes the smaller firms to mostly rely on intermediate inputs and limit their use of carbon-intensive factors (see Figure 10b). This indicates that the total emissions of small inland firms are extremely low (see Figure 8e), and accordingly the total emissions per output are also low (see Figure 8f) since the small amount of production is sustained mostly by intermediate input use. Likewise, larger firms source inputs from other firms via production networks. However, these firms are more profitable to invest on



(a) Carbon-intensive factor intensity

(b) Share of abatement investments in total expenditures on emission reduction

Figure 16: Factor intensity and the share of abatement investment of total firms

abatement since the relative price of carbon-intensive factors can be minimized via the reduction of tax payments. Therefore, these firms utilize relatively greater amount of carbon-intensive inputs than intermediate inputs, and thus emit comparatively more pollution: the total emissions increase as the output level of firms enlarges, and the greater scale of abatement investment augments the usage of carbon-intensive factors. Figure 15 proves this argument. It describes that the high-end inland firms intensively utilize carbon-intensive inputs (Figure 15a), and this is positively correlated with the greater share on abatement investments (Figure 15b).

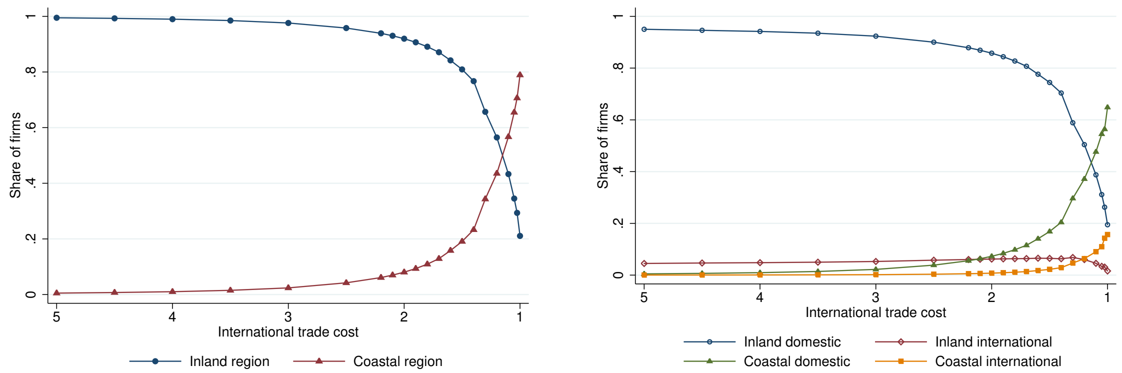
We have discussed the variations in emission intensities across firms within the coastal and inland regions. Figure 16 allows us to compare the intensity of inland and coastal firms in utilizing carbon-intensive inputs, and the share of abatement investments in total expenditures on reducing emissions. Both Figures 16a and 16b show that the high-end inland firms use carbon-intensive inputs most intensively and exhibit the greatest share of abatement investments among all firms in the economy. In contrast, coastal firms overall utilize intermediate goods relatively more intensively compared to inland firms by investing a greater share of their expenditure on purchasing intermediate goods from upstream firms. The difference in firms' behaviors between inland and coastal regions induces the heterogeneity in emission intensities as shown in Figure 8b.

4.4 Trade Liberalization, Firm Distribution and Regional Environmental Quality

We have thus far studied the role of networks in determining firm-level total emissions and emission intensities. The key result was that total emissions are positively correlated with the consumption of carbon-intensive inputs, which increases from the enlarged scale of production and from the general equilibrium effect of abatement investments. As coastal firms tend to produce a greater amount of output, and the general equilibrium effect is stronger compared to inland firms due to larger abatement investments, coastal firms become “dirtier” in the aggregate than inland firms. However, coastal firms are “cleaner” per unit of output than inland firms largely due to their outsourcing activities. In contrast to abatement investments which ironically have the potential to increase emissions, outsourcing behaviors enable firms to replace carbon-intensive inputs with outsourced intermediate goods, and thus unambiguously lead to a reduction in emissions. Therefore, coastal firms are able to stay cleaner per unit of output as outsourcing sustains the scale of production but restrains the increase of emissions entailed by production activities. In this section, we numerically demonstrate the effect of international trade cost reductions on the distribution of firms between inland and the coastal regions. As illustrated in Section 3.5, firms are initially assumed to be located in the inland, but upon deciding to stay in the market, firms decide whether to establish production networks with foreign firms, and to relocate towards the coastal regions under exogenously determined fundamentals and trade costs. After we discuss the distribution of firms across regions, we study how firm-level carbon emissions and emission intensities turn into aggregate regional-level emissions and emission-intensities.

4.4.1 Trade Cost Reductions and the Coastal Agglomeration of Firms

The Statistics of U.S. Businesses (2013) provide the stylized fact that around 80% of manufacturing firms are located in the coastal states of the U.S. Therefore, we choose the benchmark distribution of firms following the data that 80% of firms are agglomerated on the coast, and further assuming that international trade is perfectly liberalized. Under this benchmark scenario, we alter the level of international trade costs and investigate the share of firms between inland and coastal regions.



(a) Share of firms across inland and coastal regions

(b) Share of firm types across inland and coastal regions

Figure 17: Trade liberalization and the coastal agglomeration of firms

Figure 17 describes the effect of trade liberalization on the distribution of firms between inland and coastal regions.[33] Figure 17a tells us that trade cost reductions encourage firms to relocate towards the coast. When international trade frictions are significantly high (e.g, when $\tau_B = 5$, 5 units of intermediate goods need to be shipped from the origin in order for 1 unit of intermediate goods to be consumed in the foreign destination) firms are disincentivized from moving to the coast because high international trade barriers lower firms' expected profitability from relocating: a majority of firms choose to stay in the inland and focus on establishing domestic networks since the matching channel with foreign firms is effectively blocked. However, as international trade costs diminish, inland firms begin to relocate towards the coast thanks to the improved expected profits arising from the enhanced prospects of establishing supply networks with foreign trade partners along with transportation cost reductions from locating in the coastal regions. We can verify that sufficiently low international trade costs induce a dramatic agglomeration of inland firms towards the coast. The reason is that a large mass of smaller and less efficient firms which would otherwise remain in the inland regions become profitable enough to bear the relocation costs thanks to the lowered international trade barriers.

Figure 17b shows in detail the types of firms locating between the two regions in response to the reduction in international trade costs. Consistent with Figure 17a, we are able to verify that the

[33] The scale of horizontal axis which describes the level of international trade costs (in the form of iceberg trade costs) is reversed in order to clearly exhibit the effect of trade liberalization on geographical distribution of firms. This setup remains throughout the rest of the paper.

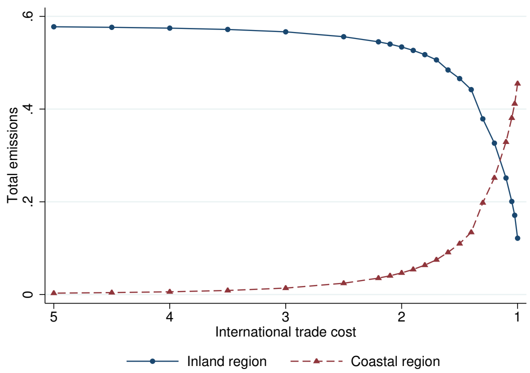
share of inland domestic firms is constantly decreasing along with trade frictions as firms are able to expect higher profits on the coast. The share of inland international firms, however, increases slightly until the international trade costs become sufficiently low. This fact indicates that when international trade costs remain relatively high even after the reduction in trade frictions, firms try to match with foreign partners while maintaining their initial location. We can further see that the portion of inland international firms is greater than that of coastal domestic and international firms when international trade barriers are high enough (greater than 2 in our example). The reason is that high trade barriers allow for only the largest and most productive firms to move to the coastal region. However, when the trade costs become sufficiently low, close enough to complete trade liberalization, inland (international) firms can anticipate greater profits from relocating to the coast. Clearly, we are able to observe that trade cost reductions sharply raise the share of coastal firms. This increase in the share of coastal firms encompasses increases in both the number of coastal domestic firms and coastal international firms. We can interpret this result as reflecting the notion that the coastal agglomeration of the largest and most productive firms exerts an attractive force on the medium-sized firms to relocate and collocate to the coastal regions.

Then, what would be the effect of the heterogeneous distribution of firms across regions on regional environmental quality? The next section addresses this question.

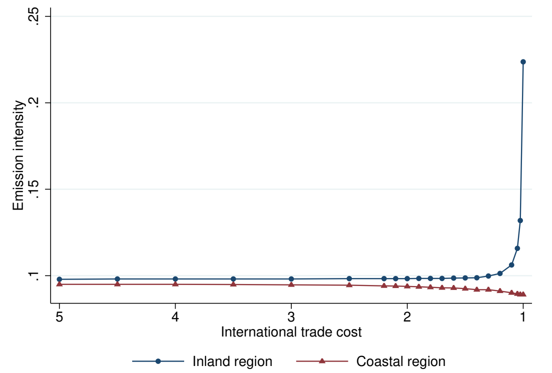
4.4.2 The Heterogeneous Distribution of Firms and Regional Environmental Quality

Based on the discussion in sections 4.3 and 4.4.1, we study how firm-level emissions and emissions intensities translate into aggregate regional environmental quality under different scenarios of international trade costs and the distribution of firms across regions. Figure 18 describes the variation in regional environmental quality corresponding to international trade cost reductions. Figure 18a tells us that the total emissions in the inland region decrease as trade becomes freer; however, the coastal region undergoes a consistent increase in the level of total emissions. The reason is that the trade cost reductions lead to more relocation of firms towards the coast. More firms and greater output production lead to more generation of pollution.

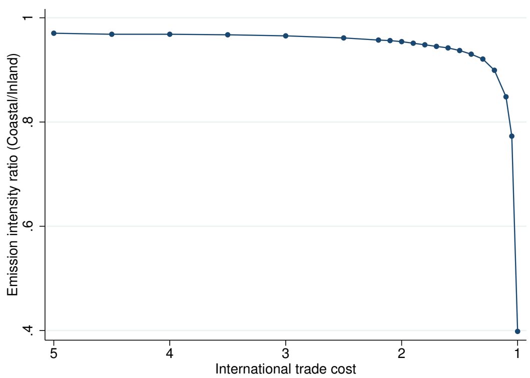
Figure 18b describes regional emission intensities and yields interesting insights. First, we can see that the coastal region is “cleaner” per unit of output regardless of the level of trade costs. The reason is due to the spatial selection of firms. The assumption that all firms start out located in



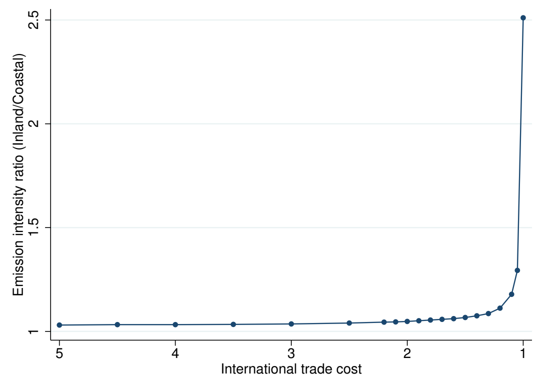
(a) Total emissions of inland and coastal regions



(b) Emission intensities of inland and coastal regions



(c) Emission intensity ratio (coastal/inland)



(d) Emission intensity ratio (inland/coastal)

Figure 18: Trade liberalization and regional environmental quality

the inland and decide whether to relocate to the coast implies that the "first movers" to the coast after the reduction in trade frictions are the largest and most efficient firms. As discussed in Section 4.3, these firms exhibit the lowest emission intensities due to greater abatement investments and outsourcing behaviors which sustain their large scale of output. Second, we are able to verify that freer international trade widens the gap in regional emission intensities between the inland and the coast. Again, this is because of the agglomeration of firms towards the coast. As a large mass of firms collocate within the coastal region, coastal firms are increasingly able to enlarge the scale of abatement investments and outsource intermediate goods. Again, this enables firms to restrain the growth of total emissions, originating from the expanded scale of production. Conversely, as barriers to trade are lowered, the inland regions witness an emigration of firms, making it more difficult for the remaining firms to source intermediate inputs. This causes the remaining firms to favor abatement investment over outsourcing, exacerbating the general equilibrium effect arising from the fall in the price of the dirty input.

Figures 18c and 18d respectively describe the relative emission ratio of the coastal and inland regions. We can reverify that coastal regions are consistently cleaner per unit of output compared to inland regions: the curve describing the emission intensity is always located below one. The negative slope and convex shape of the curve indicate that coastal regions become increasingly cleaner per unit of output as a result of trade cost reductions. Figure 18d conveys the opposite message that inland regions are consistently dirtier per unit of output than coastal regions, and this pattern worsens due to trade liberalization. The significant changes in relative regional emission intensities depicted in Figures 18c and 18d are closely associated with the stark coastal agglomeration of inland firms at sufficiently low international trade costs. Furthermore, the large mass of inland firms which ultimately relocate to the coast are the largest and the most productive ones among the remaining inland firms. Thus, losing these types of firms implies that only the smallest and least productive firms are left in the inland regions, which in turn leads to a significant rise in the inland emission intensity.

4.5 The Relative Effect of Production Networks on Regional Environmental Quality

We have thus far discussed the effect of trade cost reductions on regional emissions and emission intensities. Freer international trade induces the coastal agglomeration of firms through the channel of firm-to-firm networks. Furthermore, we have shown that international trade cost reductions have an effect of widening the gap in environmental quality between inland and coastal regions both in terms of total emissions and emission intensities. The majority of emissions are concentrated in the coastal regions due to firms' agglomeration; however, coastal emission intensities drop while inland emission intensities sharply rise because of the availability of outsourcing activities as discussed in section 4.3.

In this section, we show the significance of considering firm-to-firm networks in our analyses by studying the relative effect of production networks in affecting regional environmental quality in comparison to a setting where production networks are absent (in this case, abatement investments are the only feasible channel through which firms are able to reduce their total emissions). We additionally consider a situation where firms obtain intermediate inputs from exogenous input-output linkages, not through the formation of production networks.

4.5.1 Production Networks Versus No Networks

We conduct an experiment which studies the relative influence of open production networks in inducing the spatial sorting of firms and heterogeneity in regional environmental quality compared to a case where the outsourcing channel is effectively closed (for simplicity, we refer to this case as the "no network" situation).

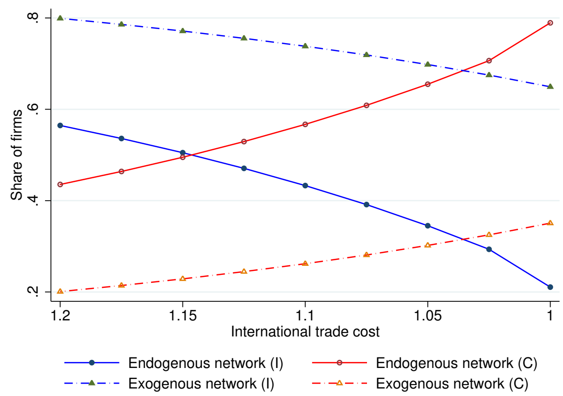
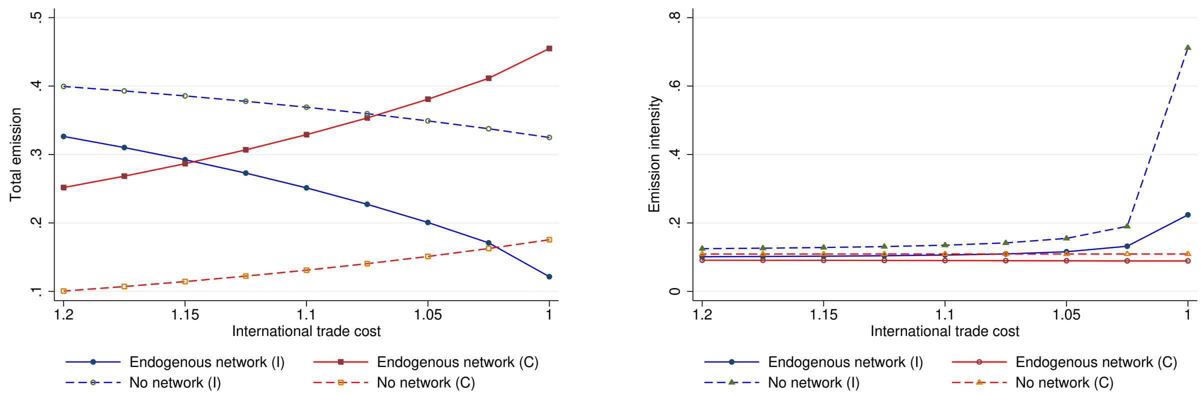


Figure 19: Spatial distribution of firms: production networks vs. no networks

Figure 19 conveys an implication that a larger number of firms are incentivized to relocate to the coastal regions when they are able to establish optimal production networks; the agglomeration force is weaker when firm-to-firm linkages are absent because the geographical distribution of firms is solely determined by the spatial sorting arising from trade liberalization. As illustrated in Figure 20a, the weaker forces of coastal agglomeration of firms in the absence of networks induces a lower concentration of total emissions in the coastal areas. The interior regions, on the other hand, are more likely to experience greater emissions due to a large number of firms remaining in the inland relative to the case with robust networks. We should interpret the result as suggesting the a possibility of underestimating (overestimating) the effect of globalization on coastal (inland) total emissions.

Figure 20b portrays the fact that ignoring the outsourcing channel of firms may induce biases in measuring the effect of trade cost reductions on regional emission intensities. Due to the absence of the networks that otherwise allow firms to substitute intermediate inputs for emission-intensive



(a) Regional total emissions: production networks vs. no networks

(b) Regional emission intensities: production networks vs. no networks

Figure 20: Regional environmental account under two different network regimes

inputs, abatement investments present the only channel through which firms can reduce their total emissions. Therefore, we observe that average emission intensities in both regions are greater than those in the case where production networks are endogenously determined. The gap in emission intensities between coastal and inland regions when trade costs become sufficiently low is smaller if firms are connected via networks. This is because lower trade barriers improve the ability of firms to search for their best supplier firms, which in turn encourage production factor substitution from emission-intensive factors to intermediate inputs.

4.5.2 Production Networks Versus Input-output Linkages

Accounting for the fact that the outsourcing activities of firms can also be modeled through firms' input-output linkages (in other words, firms purchase intermediate goods from the average firm in the industry; we refer to this as an exogenous network), we explore how intermediate goods trade via input-output linkages differs from intermediate trade conducted within endogenous production networks in affecting regional environmental quality.[34]

First, we study the spatial distribution of firms. Figure 21 portrays the fact that trade liberalization encourages firms to relocate towards the coastal regions whether networks are endogenous or exogenous; the solid lines describe how the share of firms in inland (blue line) and coastal regions

[34] In this exogenous networks case, we calculate the average of the matching probability of firms and assume that all firms share the probability in common.

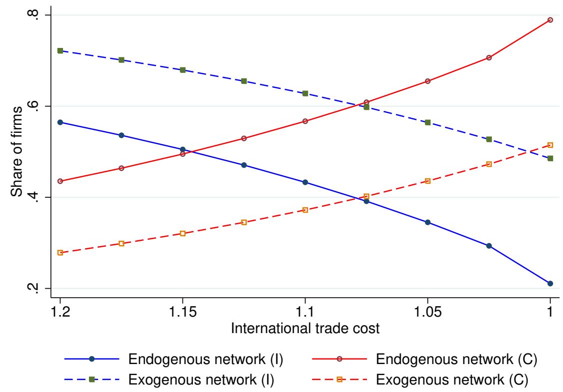
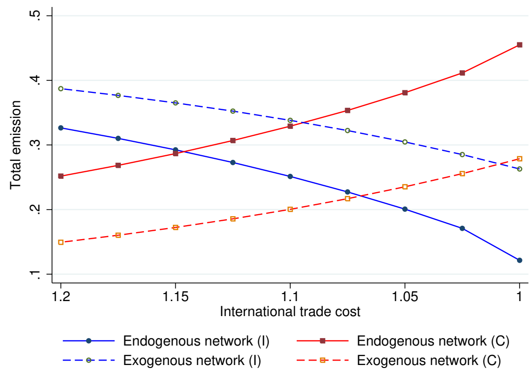


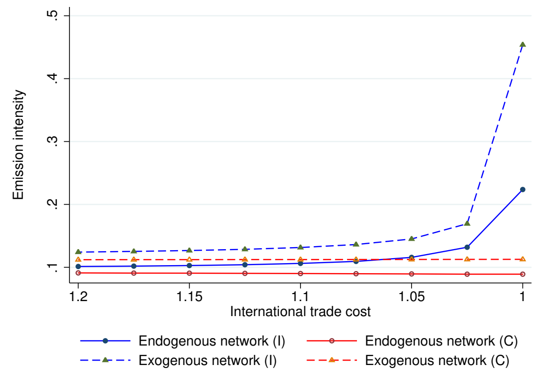
Figure 21: The spatial distribution of firms: production network vs. input-output linkage

(red line) varies with respect to different values of international trade costs when firms are linked by production networks, while the dashed lines illustrate the share of firms in two regions when firms obtain intermediate goods from an exogenous network. We can verify that, at all levels of trade costs, the agglomeration forces are significantly stronger when firms optimally choose their trade partners compared to the case where firms trade with the average firm in the industry. It is also observable that globalization magnifies the forces encouraging firms to relocate in the context of endogenous production networks.

We can find the reason for this difference by considering the intensive and extensive margins of firms. When firms obtain intermediate inputs from input-output linkages, it implies that the total mass of firms with which each firm is able to trade is fixed. The role of trade cost reductions, therefore, is to improve firms' profitabilities by enlarging the volume of trade between a given set of firms; in this case, trade liberalization acts solely along the intensive margin of firm-level trade. However, production networks allow firms to expect greater profits from moving to the coast because of the improved likelihood of establishing supply relationships with a larger number of foreign trade partners; in this case, globalization also impacts firm-level trade along the extensive margin. In other words, larger and efficient firms can not only trade with foreign firms of similar sizes and productivity levels to their own, but are also able to initiate production relationships with smaller firms abroad thanks to trade cost reductions. Hence, relocating is even more profitable when networks can be chosen endogenously, and the fact that close connections between smaller firms and the high-end firms exist within a country again implies that the coastal agglomeration of larger firms encourages smaller firms to collocate within the same region.



(a) Regional total emissions: production network vs. input-output linkage



(b) Regional emission intensities: production network vs. input-output linkage

Figure 22: Regional environmental account under two different network regimes

Second, we explore how the geographical distribution of firms affects regional total emissions and emission intensities. As discussed earlier, Figure 22a shows that regional total emissions are closely related to the spatial distribution of firms. We can verify that coastal regions experience greater total emissions when trade costs are sufficiently low under two different network regimes. However, the figure suggests that we may underestimate the regional differences in total emissions if endogenous production networks are not considered.

Figure 22b depicts the opposite result for the case of emissions intensities. If networks are exogenously formed, then regional differences in emissions intensities will be overestimated relative to when mutually beneficial relationships between firms can be endogenously established. If firms exogenously outsource intermediate inputs from the average firm in an industry, it implies that the outsourcing channel is comparatively slim, which in turn raises regional emission intensities.

The key components which induce regional heterogeneity in environmental quality we have studied throughout this paper were the intermediate good trade between firms and the coastal agglomeration of firms. The findings in this section tell us that exogenous firm-to-firm trade in intermediate inputs is not enough to correctly capture the effect of globalization on spatial differences in environmental quality.

In the next section, we compare the three distinct network regimes we have explored. From this exercise, we are able to clearly observe the necessity of considering endogenous networks in our analyses.

4.5.3 Regional Environmental Accounts Under Three Different Network Regimes

The discussions thus far enable us to compare the effect of trade liberalization on the spatial distribution of firms and regional environmental accounts under three different network regimes.

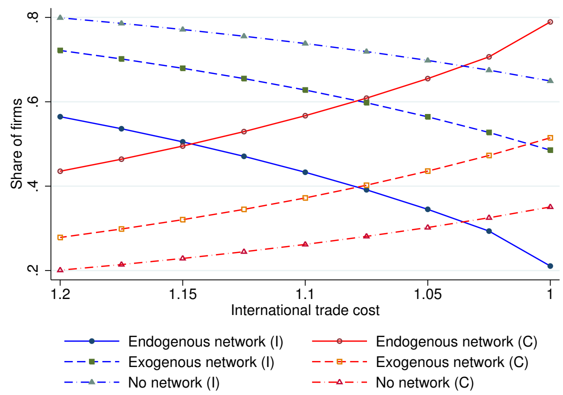
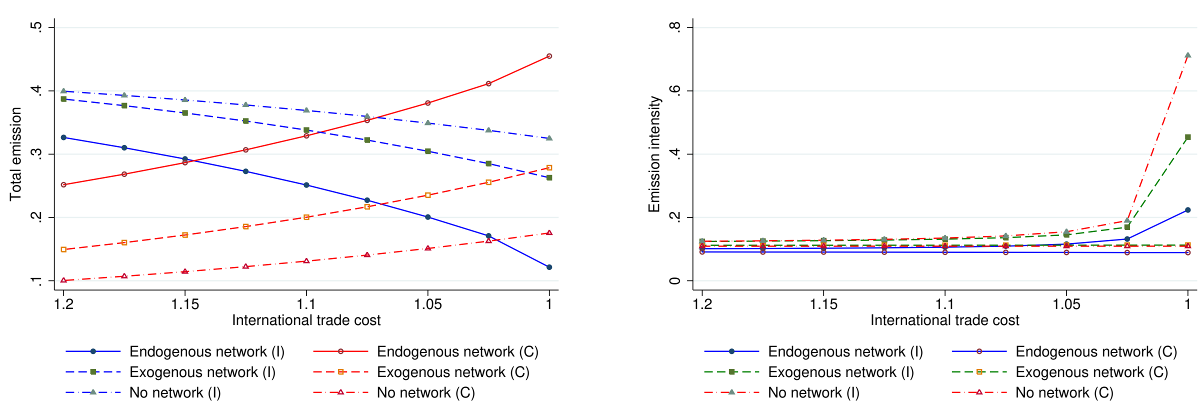


Figure 23: Spatial distribution of firms: production network vs. input-output linkage vs. no network

Figure 23 depicts how coastal agglomeration forces differ based on the degree to which firms are able to access production networks. Greater accessibility of networks leads to more firms collocating in the coastal regions where they are able to minimize transport costs to foreign markets, and globalization magnifies this effect.



(a) Regional total emissions: production network vs. input-output linkage vs. no network

(b) Regional emission intensities: production network vs. input-output linkage vs. no network

Figure 24: Regional environmental accounts under three different network regimes

The impact of coastal agglomeration on regional total emissions is thus straightforward. Figure 24a shows that the largest level of emissions occur in the coastal regions when firms are linked via production networks due to the forces of agglomeration being strongest in this setting. Figure 24b further illustrates a consistent pattern wherein closer firm linkages lower emission intensities in both inland and coastal regions. We are also able to reverify the finding that robust production relationships mitigate the divergence in regional emission intensities arising from globalization. From these comparisons, it becomes evident that consideration of production networks is imperative in properly studying the effect of trade liberalization on regional environmental quality.

5 Conclusion

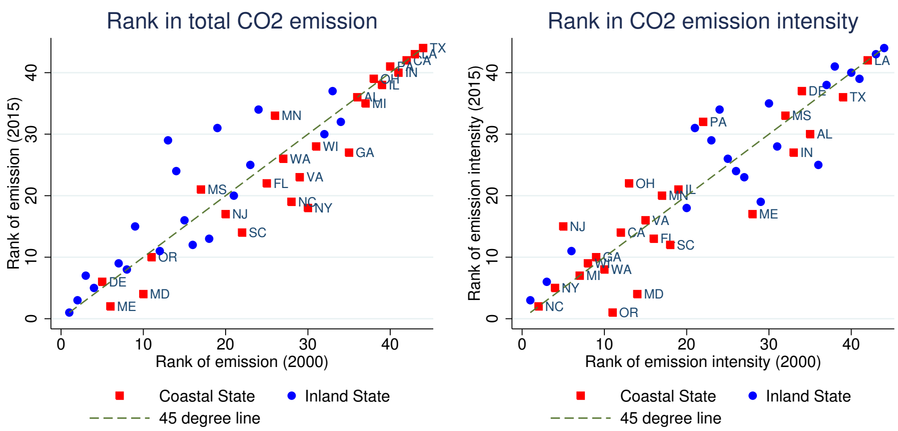
This paper studies the theoretical mechanism through which international trade cost reductions induce regional heterogeneity in environmental quality when firms are linked through production networks. We find that decreases in the barriers to international trade, coupled with the existence of firm linkages, can be driving forces in causing the allocation of a greater share of pollution in the coastal regions as the coastal agglomeration of firms is encouraged. However, coastal regions can lower their emission intensities thanks to expansions in the levels of firms' abatement investments and outsourcing activities. As firms are increasingly able to find their best trade partners from whom they can outsource intermediate goods at lower prices, firms' profitabilities accordingly improve and thus firms are able to bear greater abatement costs. Combined with these expanded abatement investments, firms are additionally able to substitute emission-intensive production factors with outsourced intermediate goods, which lowers emission intensities even further. Inland firms also experience expanded production and are able to lower their emissions as they participate in networks. However, the networks that inland firms are able to establish is limited because a majority of firms are located on the coast, and establishing networks across regions is costly. Therefore, inland firms mostly rely on abatement investments, potentially leading to increased use of emission-intensive inputs from the general equilibrium effect that we characterize. This results in relatively greater regional emission intensities in inland compared to coastal regions.

The framework introduced in this paper can be extended in several potentially useful ways. First, we have imposed the stringent assumption that emissions are only generated by the carbon-intensive input use. However, in practice, pollution is emitted during the entire process of manufacturing; the role of intermediate goods in generating pollution emissions is unexplored in this paper. If certain varieties of intermediate goods are particularly energy-intensive with regard to the way in which they are transformed into final output, then outsourcing activities might not necessarily reduce total emissions of firms and the impact of outsourcing in reducing emissions might be attenuated. Thus, future research might emphasize the effect of domestically and globally sourced intermediates on pollution. Second, this paper limits its focus on the initiation of firm relationships. However, it has been empirically established that most buyer-seller pairs are terminated within two years, and importing firms maintain their search for replacement suppliers, which are able to replace the dropped varieties (see (Bernard et al., 2018)). If larger and more efficient firms are able to purchase cleaner intermediate goods via the wider scope of their production networks and better searching capabilities (compared to smaller firms, which also outsource intermediates but which in the real world might import dirtier intermediate goods), the heterogeneity in emission intensities between inland and coastal regions can be magnified over time. Thus, this paper can be extended to study the dynamic impacts of the initiation and termination of intra-firm relationships on the regional environment while also considering the role of outsourced intermediate goods on pollution generation.

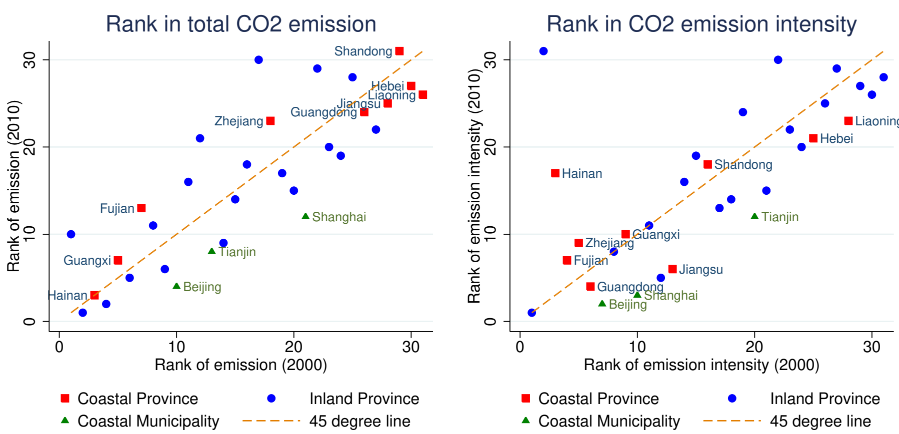
Appendix

A. Time-consistent Pattern of Heterogenous Regional Environmental Quality

We have observed the contrasting patterns of total emissions and emission intensities across regions within countries. In this section, we show that those patterns are time consistent.



(a) Rankings of US states in total CO_2 emissions and emission intensities, 2000 versus 2015



(b) Rankings of China provinces in total CO_2 emissions and emission intensities, 2000 versus 2010

Figure 25: Regional rankings in total CO2 emissions and emission intensities in the U.S. and China

Figure 25 tells us that the reversed pattern of total carbon emissions and regional carbon emission intensities has been consistent over decades in both the U.S. and China. Figure 25a describes the heterogeneous distribution of emissions and emission intensities between inland and coast by illustrating the ranking of each state in an ascending order; "dirty" states are ranked higher. We can observe that coastal states (red dots) are, on average, ranked lower in terms of their emission intensities, but vice versa for the total emissions. Figure 25a additionally shows that the patterns are consistent over time. The fact that each observation is located near the 45 degree line implies that there is little change in ranking between 2000 and 2015 with respect to total emissions and emission intensities across states. Figure 25b has qualitatively the same implication. We can see that coastal provinces (in particular, Guangdong, Zhejiang, Fujian and Jiangsu) in China consistently generate greater total emissions compared to interior provinces; however, they have been "cleaner" per value-added compared to inland regions for almost two decades.

B. Production Networks as an Alternative Channel Inducing Regional Differences in Environmental Quality

We have made the argument that coastal firms' outsourcing activities via production networks can be one of the channels through which freer international trade induces the heterogeneous distribution of emission intensities between inland and coastal regions. However, several concerns can be raised with regard to our argument. First, it is possible to counter that comparatively lower emission intensities in the coastal regions may have been induced by relatively more stringent environmental regulations in the coastal areas. It is true that environmental policy is a crucial factor in creating the regional heterogeneity of total emissions and emission intensities. However, we find evidence that there still exists unexplained variation in emission intensities across inland and the coast if we consider the historical environmental regulation regime in China. According to Wang (2013), China was under the Seventh and Eighth Five-Year Plans from 1986 to 1995. During this time period, China imposed relatively stringent environmental regulations on inland provinces in order to encourage the economic growth of coastal provinces. We can see from Figure 26 that major Chinese coastal provinces such as Guangdong, Zhejiang and Fujian have been the "cleanest" regions nearly for two decades (1991-2010) – provinces with greater emission intensities are ranked higher – in emission intensities even when the Seventh and Eighth Five-Year Plans were implemented. If the hypothesis that stricter environmental regulations have caused lower emission intensities in the

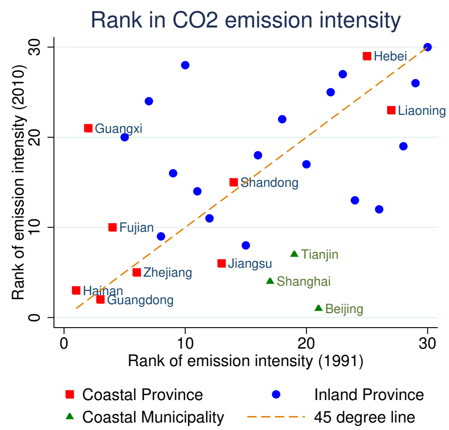


Figure 26: Rankings of Chinese provinces in total CO_2 emissions and emission intensities, 1991 versus 2010

coastal regions holds, the coastal provinces such as Guangdong, Fujian and Zhejiang should have exhibited greater emission intensities during the time periods when the two Five-Year Plans were enacted.

Second, it is also plausible to argue that the difference in industrial composition across inland and the coastal regions is the driver causing geographical heterogeneity in emission intensities: the reason why inland regions experience greater emission intensities compared to the coast is because emission-intensive industries tend to locate in interior regions. It is indeed important to consider the characteristics and the location of energy-intensive industries in order to make a clear causal statement about the effect of firms' outsourcing activities on their emission intensities. In order to alleviate this potential concern, we examine CO_2 emissions of non-energy intensive manufacturing sectors. Interestingly, we are still able to observe the consistent patterns of our interest in the U.S. over time even after eliminating emissions from the energy-adjacent sectors. For example, Figures 1a and 1c introduced earlier respectively depict the total CO_2 emissions and emission intensities of each state from the non-energy intensive manufacturing sectors in the U.S.[35] It is also possible to find suggestive evidence for China that industrial composition across regions may not be the only channel generating the heterogeneous distribution of carbon emission intensities between inland and the coast regions. Batisse (2005), for instance, studies the location of manufacturing in China and finds that Xinjiang, Yunnan, Shanxi, Heilongjiang – all inland provinces – and Hainan (a southern

[35] Petroleum and coal products manufacturing, chemical manufacturing, plastics and rubber products manufacturing are excluded in deriving the maps of regional CO_2 emissions and emission intensities.

island) each tend to specialize in natural resource-oriented industries. However, Hainan, from which Guangdong (a southern coastal province) obtains natural gas, exhibits lower emission intensity compared to aforementioned interior provinces. Similarly, Beijing, Tianjin, Shanghai, Zhejiang and Guangdong – coast municipalities and provinces – and Hubei, an interior province, tend to focus on processing agricultural and assembling intermediate goods into final products as their main industrial activities. Despite the similarity in industrial composition among the regions, we still observe profound regional difference in CO_2 emission intensities.

Lastly, technological differences across regions can be another mechanism that underlies the geographical environmental heterogeneity. Innovation is surely an important channel in affecting environmental quality; however, we are able to find an illustrative example from China that technical differences across regions do not provide a sufficient explanation for the regional differences in emission intensities. According to the Statistics Portal which provides information about internal research and development (R&D) spending in Chinese provinces in 2016, coastal provinces and municipalities, in general, spend greater share of their state GDP on R&D compared to inland provinces; Jiangsu, Shandong and Guangdong, for example, concentrate more than 2% of their GDP on R&D whereas Yunnan, Xinjiang and Qinghai allocate less than 0.5% of their GDP on R&D. However, we still observe that Shandong, the second ranked province in China in terms of the share of GDP (2.08%) spent on R&D, exhibit higher emission intensities compared to other coastal provinces such as Guangdong and Fujian which respectively allocate 2.07% and 1.35% of their local GDP.

We have thus far discussed three possible channels which may also induce the heterogeneous patterns of carbon emission intensities between inland and coastal regions. We acknowledge that environmental policies, industrial composition and innovation serve crucial roles in affecting regional environmental quality; however, there can be many other mechanisms which remain under-investigated. This paper studies one of these heretofore unexplored - yet still important - channels particularly the inter-firm trade through production networks.

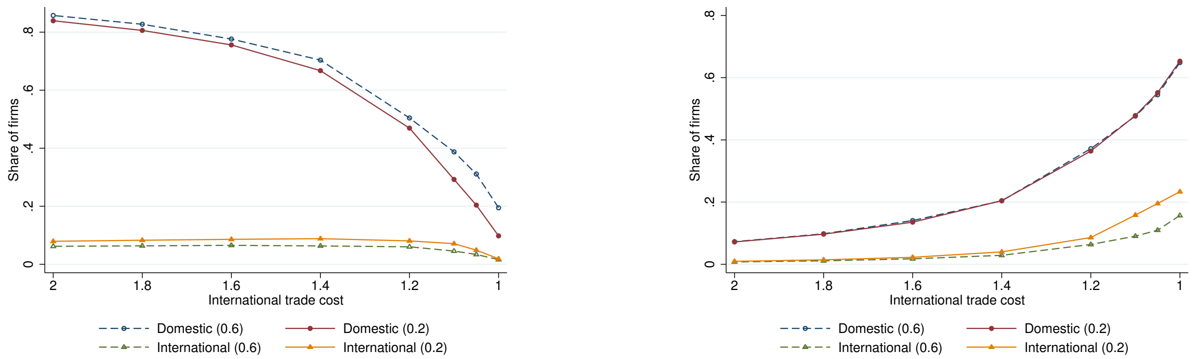
C. Extensions

In this section, we examine some of the fundamental assumptions of our model to consider the role they play in determining the magnitude and direction of our results. To do this, we extend the model in several important ways. First, we consider the case where the average relationship costs between home and foreign firms become identical to the level of mean domestic relationship costs in conjunction with trade liberalization. Second, we study the effect of network accessibilities of firms on the country and regional-level environmental account (i.e., total emission and emission intensity). Lastly, the interplay of trade liberalization and network accessibilities of firms in affecting regional environmental quality is investigated.

C.1 Mean Foreign Relationship Cost Reduction and Regional Environmental Quality

The fact that countries are able to freely trade implies that firms can find trade partners with fewer frictions. Thus, we investigate how the reduction in relationship costs between home and foreign firms affect the geographical distribution of firms and the regional environmental quality. As we have seen in the previous section, the most dramatic changes in firms' agglomeration, regional total emissions and emission intensities take place in the case where the international trade costs are between 1 and 2. We therefore limit our attention to this range of values for trade barriers, and explore the consequences of a decline in average foreign relationship costs (ψ_2) to the extreme case where they become equal to mean domestic relationship costs (ψ_1). We consider variation in two elements comprising the costs of forming a relationship with a foreign firm: (a) international trade costs, and (b) mean foreign relationship costs. By focusing on trade costs in the interval from 1 to 2, we compare the share of domestic and international firms in inland and coastal regions when the average foreign relationship costs are 0.6 (the benchmark level) versus 0.216, which is equal to the value for mean domestic relationship costs (i.e., $\psi_1 = \psi_2 = 0.216$).

Figure 27a first shows how the share of inland domestic and international firms vary with respect to international trade frictions and mean foreign relationship costs. The benchmark situation where relationship costs are equal to 0.6 is plotted with a dashed line. We can see from the figure that the relative share of international firms in the inland is greater when the relationship costs are



(a) Share of inland firms by type

(b) Share of coastal firms by type

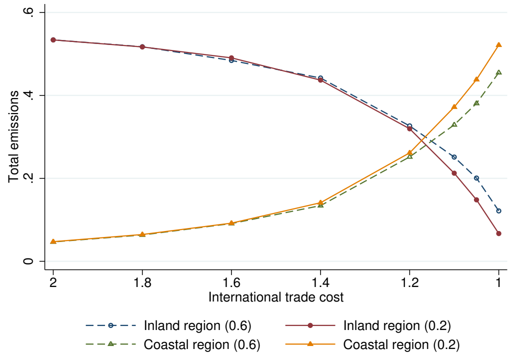
Figure 27: Share of firms in inland and coastal regions

low compared to the benchmark. The reason is that trade with foreign firms is facilitated when domestic firms are able to establish production networks with foreign trade partners at a lower cost. When international trade costs are sufficiently low (i.e., less than 1.2 in the figure), the shares of both domestic and international inland firms in the total mass of firms diminish because relocation to the coast becomes more profitable for high-end inland firms.

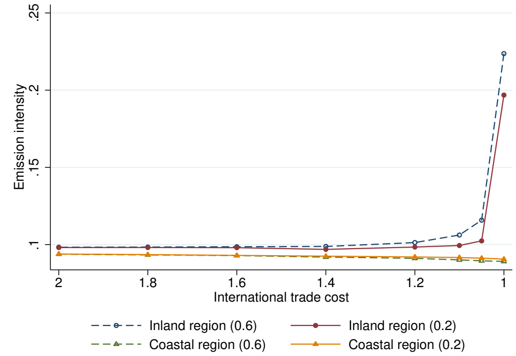
Likewise, we can see from Figure 27b that the share of coastal international firms increases when relationship costs are small. Again, this is because firms yield more profits from trading with firms abroad when the matching cost with foreign firms is low. Figure 27b additionally portrays the coastal agglomeration of inland firms. The fact that there is little change in the share of coastal domestic firms after the reduction of mean foreign relationship costs (at all levels of international trade costs) implies that the the agglomeration of inland firms to the coast occurs as a result of the decline in these costs.

All in all, Figure 27 conveys two important messages. First, the lowered mean foreign relationship cost alters the share of domestic and international firms. The share of international firms increases while the opposite holds for the share of domestic firms. Second, the reduction in relationship costs also leads to the agglomeration of firms towards the coast in a manner similar to the one engendered by trade liberalization. We next turn our focus to the impact of the distribution of firm types on regional environmental quality.

Figure 28a depicts the divergence of total emissions between inland and coastal regions. As previously discussed, the reduction in foreign relationship costs encourages firms to collocate in



(a) Divergence of regional total emissions



(b) Divergence of regional emission intensities

Figure 28: Foreign relationship cost reductions and regional environmental quality

the coastal regions. Therefore, coastal areas undergo increased total emissions for a given level of international trade costs, whereas inland regions experience decreased emissions due to the loss of firms. The composite effects of freer international trade and the reduction of relationship costs increasingly dichotomize the allocation of total emissions between the inland and the coast.

Interestingly, we are able to find the opposite pattern in emission intensities. Figure 28b describes that the divergence in regional emission intensities due to freer international trade becomes weaker when firms are able to easily establish production networks with foreign firms. The result may seem counterintuitive. Why does the lowered relationship costs not magnify the effect of freer international trade on emission intensities? We find the answer from considering the share of domestic and international firms in the respective regions. We learned that the main effect of lowered relationship costs is to increase the share of international firms. The reason why emission intensities in inland region drop for any level of international trade costs is because of the increased share of international firms. International firms are able to increase their abatement investments because of their higher profitability, and more importantly, outsource greater amount of intermediate inputs via networks.

Then, how can we understand the increased emission intensities in the coastal region? It is true that the share of international firms on the coast expands as foreign relationship costs fall. However, the impact of this is only marginal, since the largest and most efficient firms are already agglomerated in the coastal region, and thus adding a few high-end inland firms does not improve emission intensities in the coastal region. In addition, even though these firms are the largest firms in the inland regions, the relocated firms are still the least productive and smallest firms on the coast exhibiting the greatest emission intensities compared to other coastal firms. Therefore, the greater agglomeration of inland firms with higher emission intensities mitigates the effect of trade cost reductions on coastal emission intensities.

C.2 Network Openness and Regional Environmental Quality

We additionally conduct numerical exercises to verify the effect of network openness on firms' location decisions and the regional environmental quality. We have studied that the characteristics of a firm's production network as determined by its linkages with other firms are the crucial factors in determining firms' optimal location decision. Therefore, we introduce a new parameter which enables us to vary the "openness" of the network: $\nu \in [0, 1]$. The openness of networks can be interpreted as the numerous impediments (such as governmental regulations or search frictions arising from the costs of gathering information about potential partners that hinder firms from finding their best trade partners) lowering the chance that firms will be able to efficiently outsource their intermediate inputs. By adopting a new "network openness" parameter, we can slightly modify equations (3.14) and (3.15) as the following:

$$\Delta(\chi) = \underbrace{\mu^{-\sigma}\delta^{\sigma-1}}_{\text{fundamental effect}} + \underbrace{\nu}_{\text{openness}} \underbrace{\left[\mu^{-\sigma}\alpha^{\sigma-1}\int_{S_\chi} m(\chi', \chi)\Delta(\chi')dG_\chi(\chi')\right]}_{\text{network effect}},$$

$$\Phi(\chi) = \underbrace{\phi^{\sigma-1}\kappa^{1-\sigma}}_{\text{fundamental effect}} + \underbrace{\nu}_{\text{openness}} \underbrace{\left[\alpha^{\sigma-1}\mu^{1-\sigma}\int_{S_\chi} m(\chi, \chi')\Phi(\chi')dG_\chi(\chi')\right]}_{\text{network effect}}.$$

In order to limit our focus on the effect of ν, we assume that international trade is perfectly liberalized and mean foreign relationship costs are identical to the mean domestic relationship costs (i.e., $\psi_1 = \psi_2$); network openness is thus the only friction that firms face in matching with other firms both at home and abroad.

Before we study the impact of network openness on regional environmental quality, we explore how the country-level emissions and emission intensities are affected by network accessibility. Figure 29 shows that the national-level total emission increases as firms become more accessible to production networks. This is because lower barriers to firm linkages enable firms to obtain production factors at lower prices from a variety of supplier firms, and at the same time, to supply

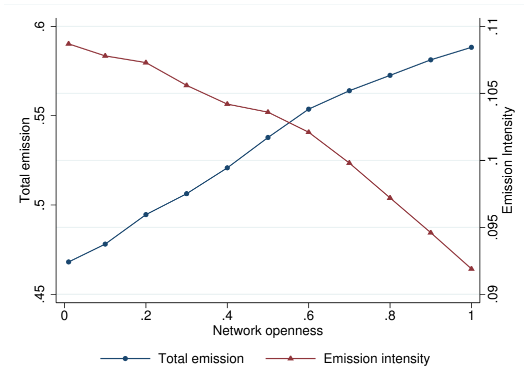


Figure 29: Network openness and a country-level total emission and emission intensity

their outputs to numerous customer firms: the scale effect. The country-level emission intensity, however, significantly drops thanks to the production networks. As we have discussed earlier, the supply chain between firms improves firms' profitability to increase abatement investments. Furthermore, it encourages firms to outsource intermediate production to other firms located within and across regions, and even to foreign firms. As a consequence, firms are able to reduce the consumption of carbon-intensive inputs, but are able to sustain their output production, which in turn lower the country-level emission intensity.

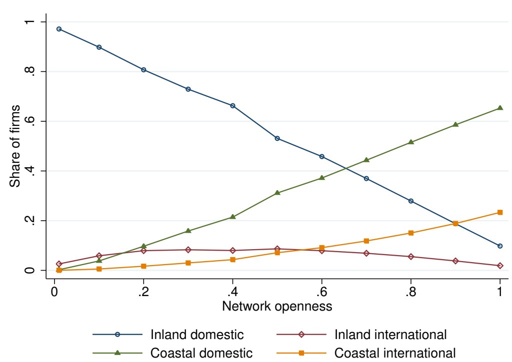
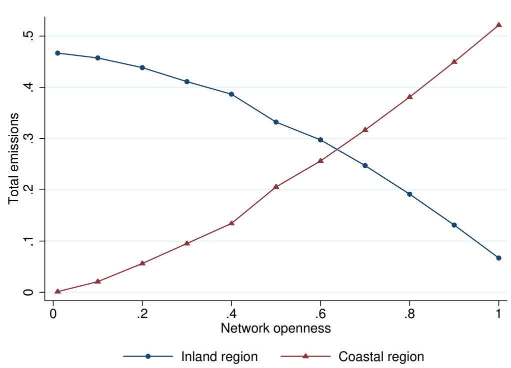
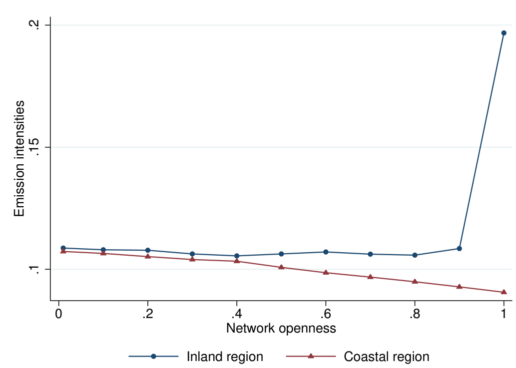


Figure 30: Network openness and coastal agglomeration of firms

We next shift our focus on the network effect on the regional environmental quality. We first consider how the distribution of firms varies by the openness of production networks. Figure 30 shows how network openness affects the share of firms by type. Similar to freer international trade and the reduction of foreign matching costs, greater network openness induces the relocation of firms towards the coastal region. We can see that the shares of inland international firms, coastal domestic firms, and coastal international firms increase as firms are increasingly able to take advantage of production networks until the point where the degree of openness rises to around 40% (i.e., only 40% of network composite effects are realized in the formulation of firms' network characteristics). The sharp decline in inland domestic firms takes place because the expanded accessibility of firms to production networks (i.e., higher ν) increases the profitability of these firms with regard to their ability to match with foreign suppliers and relocate to the coast: the high-end inland domestic firms become internationals, the high-end inland internationals become coastal domestics, and finally, the most competitive coastal domestics become international firms. We have seen in Figures 17b and 27a that the share of inland international firms begins to decrease as international trade barriers decline. Similarly, we can observe from Figure 30 that the share of inland international firms begins to decline as firms' are faced with more accessible networks because relocating towards the coastal regions becomes more attractive to firms. The decline in the share of inland domestics and internationals is mirrored by sharp rises in the share of coastal firms. We can also clearly see that this increase in the proportion of coastal international firms is accompanied by a greater increase in the proportion of coastal domestic firms. This implies that the robustness of firm-linkages is the channel through which the relocation of efficient inland firms to the coast affects the relocation of remaining smaller inland firms: the geographical movements of the largest and the most productive firms increase the incentives of smaller firms to collocate with their best trade partners by relocating towards the coastal region.



(a) Network openness and regional total emissions



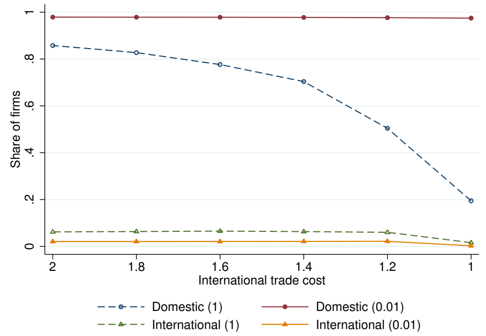
(b) Network openness and regional emission intensity

Figure 31: Network openness and the environment

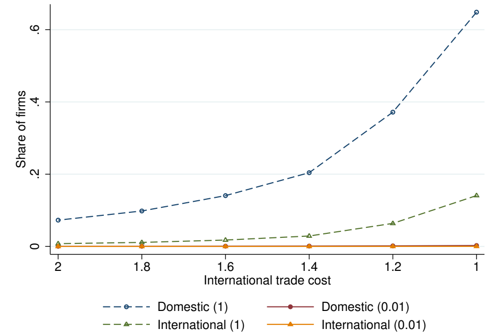
Figure 31 illustrates how the degree of network openness influences regional total emissions and emission intensities. Consistent with the results of previous experiments, Figure 31a describes that the largest shares of total emissions are concentrated in the coastal regions as firms are increasingly able to match with other firms. Again, this is closely related to the coastal agglomeration of firms depicted in Figure 30. Figure 31b shows the variation in emission intensities between inland and coastal regions. We can easily verify the figural similarity with Figures 18b and 28b in that coastal regions steadily become cleaner per output whereas the environmental quality in inland regions deteriorates as network accessibility improves. The sharp increase in emission intensities of inland regions at values of network openness approaching 100% (i.e. when $\nu \to 1$) arises when the high network accessibility spurs the high-end inland firms' relocation to the coast, and leaving only the smallest, least productive firms in the inland region. The impact of these high-end inland firms' relocation on the coastal emission intensities is comparatively marginal, however, since a large share of productive and large firms are already agglomerated in the coastal region.

C.3 Network Openness, International Trade Cost Reductions and Regional Environmental Quality

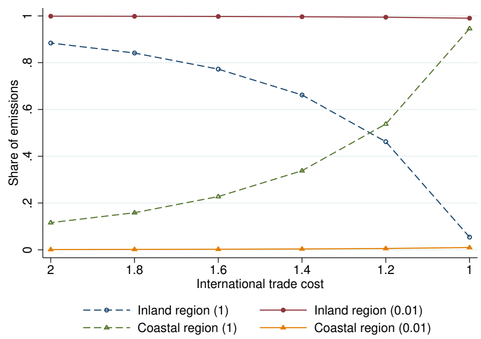
In this section, we study the interplay between reductions in international trade costs and the degree of network openness. Figure 32 shows the effect of networks on firms' location and regional environmental quality over an interval of international trade costs. Figures 32a and 32b portray the fact that most firms maintain their status as inland domestic firms as they lose accessibility to networks for any level of international trade costs: under this scenario the coastal agglomeration of firms does not take place. This is because the effect of trade liberalization is manifested through the networks, which implies that firms are more significantly affected by the degree of network openness (the first-order effect) than the implicit trade liberalization effect (the second-order effect). The implication for regional emissions is clear. Emissions are concentrated in the inland region as the majority of firms do not relocate to the coast (Figure 32c). Figure 32d tells a more nuanced story. It illustrates that both coastal and inland regions experience an increase in their emission intensities when networks are less accessible. This is because the absence of networks impedes firms' ability to outsource intermediate goods from trade partners. The most interesting part of this result is the reversal in inland emission intensities that materializes when international trade costs are



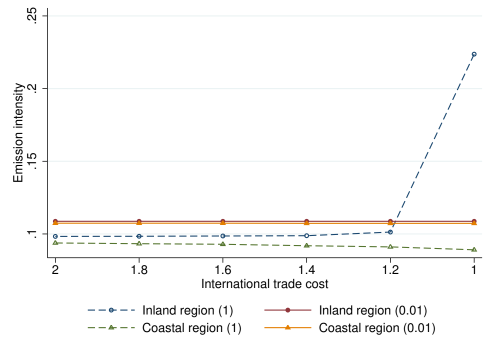
(a) Share of inland domestic and international firms



(b) Share of coastal domestic and international firms



(c) Regional total emissions



(d) Regional emission intensities

Figure 32: Distribution of firms and the environment by degree of network openness and level of international trade cost

sufficiently low. A plausible explanation for this arises when we consider the composition of firms within inland regions. We learned that the reason for the sharp increase in inland emission intensities was due to the relocation of the largest and most productive (remaining inland) firms towards the coast. In other words, only the least productive and smallest firms tend to locate in the inland regions in the presence of networks with 100% accessibility, and the scale of abatement investment of these firms is small because of their low profitabilities. However, the relocation of inland firms towards the coastal regions barely occurs in the absence of networks. This means that large and efficient firms are located in inland regions, and thus a higher level of abatement investments are undertaken. As a consequence, the previously observed jump in emission intensities fails to manifest itself. Interestingly, this result implies that the environmental quality of inland regions in emission intensities can be markedly improved in the absence of networks when international trade barriers are sufficiently low: firm-linkages do not improve environmental quality of inland regions under trade liberalization. Put differently, the existence of production networks is the catalyst by which regional heterogeneity in environmental quality is determined.

D. Derivations of Equations

D.1 Equation (3.14)

To derive the network demand of a supplier firm, we begin with the selling χ- firm's market clearing equation and substitute in the customer firms' ($x(\chi,\chi') = X(\chi')\eta(\chi')^{\sigma}p(\chi',\chi)^{-\sigma}$) and household demand ($x_H(\chi) = \Delta_H \delta^{\sigma-1} p_H(\chi)^{-\sigma}$) equations:

$$
\begin{aligned}
X(\chi) &= x_H(\chi) + \int_{S_\chi} m(\chi',\chi)x(\chi',\chi)dG_\chi(\chi') \\
&= \Delta_H \delta^{\sigma-1} p_H(\chi)^{-\sigma} + \int_{S_\chi} m(\chi',\chi)X^D(\chi')\eta^D(\chi')^{\sigma}p^D(\chi',\chi)^{-\sigma}dG_\chi(\chi')
\end{aligned}
$$

Now substitute in the selling firm's optimal price ($p_H(\chi) = p(\chi',\chi) = \left(\frac{\sigma}{\sigma-1}\right)\eta(\chi) \equiv \mu\eta(\chi)$):

$$
\begin{aligned}
X(\chi) &= \Delta_H \delta^{\sigma-1}\mu^{-\sigma}\eta(\chi)^{-\sigma} + \int_{S_\chi} m(\chi',\chi)X(\chi')\eta(\chi')^{\sigma}\mu^{-\sigma}\eta(\chi)^{-\sigma}dG_\chi(\chi'), \\
&= \mu^{-\sigma}\eta(\chi)^{-\sigma}\left[\Delta_H \delta^{\sigma-1} + \int_{S_\chi} m(\chi',\chi)X(\chi')\eta(\chi')^{\sigma}dG_\chi(\chi')\right], \\
\Delta_H^{-1}X(\chi)\eta(\chi)^{\sigma} &= \mu^{-\sigma}\left[(\delta)^{\sigma-1} + \int_{S_\chi} m(\chi',\chi)\Delta_H^{-1}X(\chi')\eta(\chi')^{\sigma}dG_\chi(\chi')\right]
\end{aligned}
$$

Now define a firm's network demand as $\Delta(\chi) \equiv \frac{1}{\Delta_H}X(\chi)\eta(\chi)^{\sigma}$; then the above equation can be simply expressed as

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

D.2 Equation (3.15)

To derive a firm's network efficiency equation, begin with the firm's unit cost function:

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

Now plug in the optimal prices of supplying χ'-firms ($p(\chi,\chi') = \left(\frac{\sigma}{\sigma-1}\right)\eta(\chi') \equiv \mu\eta(\chi')$):

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

If we define the firm's network efficiency as $\Phi(\chi) \equiv \eta(\chi)^{1-\sigma}$, then we are able to derive the following result:

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

D.3 Equation (3.26)

As firms choose their optimal abatement investments which maximize profits, we need to consider total profits first. The total profit of the χ-firm can be calculated by the subtraction of total costs required to produce intermediate outputs and abatement investments from the total revenue by selling intermediate goods to households and firms in the network:

$$\Pi(\chi; f_A(\chi)) = x_H(\chi)p_H(\chi) + \int_{S_\chi} m(\chi',\chi)x(\chi',\chi)p(\chi',\chi)dG_\chi(\chi') - X(\chi)\eta(\chi) - f_A(\chi).$$

Equations (3.2), (3.8) and (3.10) allow us to extend the above equation as

$$\Pi(\chi; f_A(\chi)) = \Delta_H\delta^{\sigma-1}p_H(\chi)^{-\sigma}[p_H(\chi)-\eta(\chi)] + \int_{S_\chi} m(\chi',\chi)X^D(\chi')\eta^D(\chi')^\sigma p^D(\chi',\chi)^{-\sigma}[p^D(\chi',\chi)-\eta^D(\chi)]dG_\chi(\chi') - f_A(\chi).$$

As $p_H(\chi) = p(\chi, \chi') = \mu\eta(\chi)$ and by equation (3.14), we can simplify the equation as the following:

$$\begin{aligned}
\Pi(\chi; f_A(\chi)) &= \Delta_H \delta^{\sigma-1}\mu^{-\sigma}\eta(\chi)^{1-\sigma}(\mu-1) + \int_{S_\chi} m(\chi', \chi)X(\chi')\eta(\chi')^{\sigma}\mu^{-\sigma}\eta(\chi)^{1-\sigma}(\mu-1)dG_\chi(\chi') - f_A(\chi), \\
&= \eta(\chi)^{1-\sigma}(\mu-1)\Delta_H\left(\mu^{-\sigma}\delta^{\sigma-1} + \mu^{-\sigma}\int_{S_\chi} m(\chi', \chi)\Delta_H^{-1}X(\chi')\eta(\chi')^{\sigma}dG_\chi(\chi')\right) - f_A(\chi), \\
&= \eta(\chi)^{1-\sigma}(\mu-1)\Delta_H\Delta(\chi) - f_A(\chi).
\end{aligned}$$

Therefore, the first-order condition is

$$\frac{\partial\Pi(\chi; f_A(\chi))}{\partial f_A(\chi)} = \frac{\partial\eta(\chi)^{1-\sigma}}{\partial f_A(\chi)}(\mu-1)\Delta_H\Delta(\chi) - 1 = 0.$$

Recall that the marginal cost of intermediate output production is

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

Therefore,

$$\begin{aligned}
\eta(\chi)^{1-\sigma} &= \phi^{\sigma-1}\kappa^{1-\sigma} + \int_{S_\chi} m(\chi, \chi')p(\chi, \chi')^{1-\sigma}dG_\chi(\chi'), \\
&= \phi^{\sigma-1}\left(\omega + \frac{t\epsilon}{f_A(\chi)}\right)^{1-\sigma} + \int_{S_\chi} m(\chi, \chi')p(\chi, \chi')^{1-\sigma}dG_\chi(\chi').
\end{aligned}$$

Thus, we have

$$\begin{aligned}
\frac{\partial\eta(\chi)^{1-\sigma}}{\partial f_A(\chi)} &= (1-\sigma)\phi^{\sigma-1}\left(\omega + \frac{t\epsilon}{f_A(\chi)}\right)^{-\sigma}\frac{-t\epsilon}{f_A(\chi)^2} \\
&= (1-\sigma)\phi^{\sigma-1}\left(\frac{\omega f_A(\chi) + t\epsilon}{f_A(\chi)}\right)^{-\sigma}\frac{-t\epsilon}{f_A(\chi)^2} \\
&= t\epsilon(\sigma-1)\phi^{\sigma-1}\left(\omega f_A(\chi) + t\epsilon\right)^{-\sigma} f_A(\chi)^{\sigma-2} > 0.
\end{aligned}$$

Plugging the result back into the first-order condition, we have

$$\Psi(\chi) \equiv t\epsilon(\sigma-1)\phi^{\sigma-1}\left(\omega f_A(\chi) + t\epsilon\right)^{-\sigma} f_A(\chi)^{\sigma-2}(\mu-1)\Delta_H\Delta(\chi) - 1 = 0,$$

such that $t, \epsilon > 0$, and $\mu > 1$.

D.4 Equations (3.27) and (3.29)

The total emissions the χ-firm can be derived by combining equations (3.18) and (3.24):

$$\begin{aligned}
e(\chi) &= \frac{\epsilon d(\chi)}{f_A(\chi)} \\
&= \epsilon X(\chi)\eta(\chi)^{\sigma}\kappa^{-\sigma}\phi^{\sigma-1}f_A(\chi)^{-1} \\
&= \epsilon\Delta_H\Delta(\chi)\left(\omega + \frac{t\epsilon}{f_A(\chi)}\right)^{-\sigma}\phi^{\sigma-1}f_A(\chi)^{-1} \\
&= \epsilon\phi^{\sigma-1}\Delta_H\Delta(\chi)\left(\frac{f_A(\chi)\omega + t\epsilon}{f_A(\chi)}\right)^{-\sigma}\left(f_A(\chi)^{\frac{1}{\sigma}}\right)^{-\sigma} \\
&= \epsilon\phi^{\sigma-1}\Delta_H\Delta(\chi)\left[\left(f_A(\chi)\omega + t\epsilon\right)f_A(\chi)^{\frac{1-\sigma}{\sigma}}\right]^{-\sigma}.
\end{aligned}$$

Thus, emission intensities of the χ-firms can simply be calculated as

$$\begin{aligned}
\Xi(\chi) \equiv \frac{e(\chi)}{X(\chi)} &= \frac{e(\chi)}{\Delta_H\Delta(\chi)\Phi(\chi)^{\frac{\sigma}{\sigma-1}}}, \\
&= \frac{\epsilon\phi^{\sigma-1}\Delta_H\Delta(\chi)\left[\left(f_A(\chi)\omega + t\epsilon\right)f_A(\chi)^{\frac{1-\sigma}{\sigma}}\right]^{-\sigma}}{\Delta_H\Delta(\chi)\Phi(\chi)^{\frac{\sigma}{\sigma-1}}}, \\
&= \epsilon\phi^{\sigma-1}\Phi(\chi)^{-\frac{\sigma}{\sigma-1}}\left[\left(f_A(\chi)\omega + t\epsilon\right)f_A(\chi)^{\frac{1-\sigma}{\sigma}}\right]^{-\sigma}.
\end{aligned}$$

D.5 Detailed Expressions of $\Delta^I(\chi;\tau_D(\chi),\tau_B(\chi))$, $\Phi^I(\chi;\tau_D(\chi),\tau_B(\chi))$ in Equation (3.37)

The network characteristics of the χ- firm are directly affected by trade frictions, and so does the variable profit. The network properties of the χ-firm can be illustrated as the following:

$$
\begin{aligned}
\Delta^{HI}(\chi;\tau_D(\chi),\tau_B(\chi)) = \mu^{-\sigma}\delta^{\sigma-1} + \mu^{-\sigma}\Bigg[& \int_{S_\chi^{HI}} \widetilde{m}\left[\Delta_H\Delta^{HI}(\chi')\Phi^{HI}(\chi)\right]\Delta^{HI}(\chi')dG_\chi(\chi') \\
& + \int_{S_\chi^{HC}} \widetilde{m}\left[\Delta_H\Delta^{HC}(\chi')\Phi^{HI}(\chi);\tau_D(\chi)\right]\Delta^{HC}(\chi')\left(\tau_D(\chi)\right)^{-\sigma}dG_\chi(\chi') \\
& + \int_{S_\chi^{FI}} \widetilde{m}\left[\Delta_H\Delta^{FI}(\chi')\Phi^{HI}(\chi);\tau_{BDD}(\chi)\right]\Delta^{FI}(\chi')\left(\tau_{BDD}(\chi)\right)^{-\sigma}dG_\chi(\chi') \\
& + \int_{S_\chi^{FC}} \widetilde{m}\left[\Delta_H\Delta^{FC}(\chi')\Phi^{HI}(\chi);\tau_{BD}(\chi)\right]\Delta^{FC}(\chi')\left(\tau_{BD}(\chi)\right)^{-\sigma}dG_\chi(\chi')\Bigg], \\
\Phi^{HI}(\chi;\tau_D(\chi),\tau_B(\chi)) = \phi^{\sigma-1}\kappa^{1-\sigma} + \mu^{1-\sigma}\Bigg[& \int_{S_\chi^{HI}} \widetilde{m}\left[\Delta_H\Delta^{HI}(\chi)\Phi^{HI}(\chi')\right]\Phi^{HI}(\chi')dG_\chi(\chi') \\
& + \int_{S_\chi^{HC}} \widetilde{m}\left[\Delta_H\Delta^{HI}(\chi)\Phi^{HC}(\chi');\tau_D(\chi)\right]\Phi^{HC}(\chi')\left(\tau_D(\chi)\right)^{1-\sigma}dG_\chi(\chi') \\
& + \int_{S_\chi^{FI}} \widetilde{m}\left[\Delta_H\Delta^{HI}(\chi)\Phi^{FI}(\chi');\tau_{BDD}(\chi)\right]\Phi^{FI}(\chi')\left(\tau_{BDD}(\chi)\right)^{1-\sigma}dG_\chi(\chi') \\
& + \int_{S_\chi^{FC}} \widetilde{m}\left[\Delta_H\Delta^{HI}(\chi)\Phi^{FC}(\chi');\tau_{BD}(\chi)\right]\Phi^{FC}(\chi')\left(\tau_{BD}(\chi)\right)^{1-\sigma}dG_\chi(\chi')\Bigg].
\end{aligned}
$$

D.6 Detailed Expressions of $\Delta^{HC}(\chi; \tau_D(\chi), \tau_B(\chi))$, $\Phi^{HC}(\chi; \tau_D(\chi), \tau_B(\chi))$ in Equation (3.42)

The network characteristics which determine the variable profit of the coastal firm are

$$
\begin{aligned}
\Delta^{HC}(\chi; \tau_D(\chi), \tau_B(\chi)) = \mu^{-\sigma}\delta^{\sigma-1} + \mu^{-\sigma}\Bigg[& \int_{S_\chi^{HC}} \widetilde{m}\left[\Delta_H \Delta^{HC}(\chi')\Phi^{HC}(\chi)\right] \Delta^{HC}(\chi') dG_\chi(\chi') \\
& + \int_{S_\chi^{HI}} \widetilde{m}\left[\Delta_H \Delta^{HI}(\chi')\Phi^{HC}(\chi); \tau_D(\chi)\right] \Delta^{HI}(\chi') \left(\tau_D(\chi)\right)^{-\sigma} dG_\chi(\chi') \\
& + \int_{S_\chi^{FC}} \widetilde{m}\left[\Delta_H \Delta^{FC}(\chi')\Phi^{HC}(\chi); \tau_B(\chi)\right] \Delta^{FC}(\chi') \left(\tau_B(\chi)\right)^{-\sigma} dG_\chi(\chi') \\
& + \int_{S_\chi^{FI}} \widetilde{m}\left[\Delta_H \Delta^{FI}(\chi')\Phi^{HC}(\chi); \tau_{BD}(\chi)\right] \Delta^{FI}(\chi') \left(\tau_{BD}(\chi)\right)^{-\sigma} dG_\chi(\chi') \Bigg], \\
\Phi^{HC}(\chi; \tau_D(\chi), \tau_B(\chi)) = \phi^{\sigma-1}\kappa^{1-\sigma} + \mu^{1-\sigma}\Bigg[& \int_{S_\chi^{HC}} \widetilde{m}\left[\Delta_H \Delta^{HC}(\chi)\Phi^{HC}(\chi')\right] \Phi^{HC}(\chi') dG_\chi(\chi') \\
& + \int_{S_\chi^{HI}} \widetilde{m}\left[\Delta_H \Delta^{HC}(\chi)\Phi^{HI}(\chi'); \tau_D(\chi)\right] \Phi^{HI}(\chi') \left(\tau_D(\chi)\right)^{1-\sigma} dG_\chi(\chi') \\
& + \int_{S_\chi^{FC}} \widetilde{m}\left[\Delta_H \Delta^{HC}(\chi)\Phi^{FC}(\chi'); \tau_B(\chi)\right] \Phi^{FC}(\chi') \left(\tau_B(\chi)\right)^{1-\sigma} dG_\chi(\chi') \\
& + \int_{S_\chi^{FI}} \widetilde{m}\left[\Delta_H \Delta^{HC}(\chi)\Phi^{FI}(\chi'); \tau_{BD}(\chi)\right] \Phi^{FI}(\chi') \left(\tau_{BD}(\chi)\right)^{1-\sigma} dG_\chi(\chi') \Bigg].
\end{aligned}
$$

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