Production Leakage: Evidence from Uncoordinated Environmental Policies *

Zhiyuan Li† Bing Lu ‡ Sili Zhou§

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Abstract

This paper documents that international trade may cause uneven distribution of opportunities and costs to countries in face of uncoordinated environmental policies. Specifically, we use exogenous introductions of national carbon taxes to study how local firms react to such shocks, especially when they make outsourcing decisions on carbon inputs. Results show that regulatory carbon taxes lead domestic firms to import more carbon products, such as cement, iron and steel, from foreign producers. Firm-level data additionally show that firms will increase their trade shares to foreign suppliers headquartered in pollution haven. Exploiting buyer-supplier relation information, we further find that domestic regulatory carbon taxes do benefit foreign carbon suppliers, helping them to, for example, expand production scales and relax financial constraints. These findings highlight the critical role that international trade play in fulfilling growth, welfare and emission reduction goals of environmental policies.

Keywords: Green Trade, Carbon Taxes, Production leakage, Global Supply Chain

JEL Classification: F18, F23, F64, H23, Q56

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†School of Economics, Fudan University.(zhyli@fudan.edu.cn).

‡School of Statistics, Beijing Normal University.(lubing@bnu.edu.cn).

§Faculty of Business and Administration, University of Macau, and Asia-Pacific Academy of Economics and Management, University of Macau (silizhou@um.edu.mo).

1 Introduction

Understanding the effects of international trade to domestic growth is tremendously important, especially when government policy starts to shift from better growth to sustainable growth recently. Most developed countries actively introduced carbon emission reduction policies to address climate risk (Acemoglu et al. 2012, 2016, Gillingham and Stock 2018, Schroeder and Stracca 2023). Yet, the literature has not provided a perfect global coordination: national governor may be inclined to impose carbon taxes unilaterally, for fear that affected local firms to arbitrage via cross-border reallocation (Laeven and Popov 2023, Ivanov et al. 2023). The implementation of carbon taxes policy eventually leads domestic firms to import more foreign goods, by which we mean a carbon leakage at the cost of local growth (Copeland et al. (2022))[1].

In this paper, we study the effect of international trade in response to the unexpected introduction of the domestic carbon tax policy using the micro-level data. Between 1990 and 2019, 25 countries imposed carbon taxes and some joined an Emission Trading Scheme (ETS) which limits the emission of carbon-intensive sectors such as cement,iron, steel etc. Those policies could reduce *territorial* carbon emission but import more carbon-intensive products abroad.

Based on this measure, we present several interesting findings. First, country-level evidence that an exogenous increase of carbon costs reduce the carbon emission domestically. The economic magnitude of this carbon tax is sizable: a country which introduced carbon tax is associated with a 15.3% average decrease in a typical country's domestic CO_2 emission as a fraction of its GDP (in 2015 US dollar). However, the consumption of carbon products is not reduced. They will import more carbon intensive products from countries with low carbon production cost. Further evidence presented by bilateral trade results suggest that the carbon imports happen to the trade partners without lax environmental protection, such as countries without carbon taxes, and high-carbon emission countries. On average, compared to low carbon emission countries, the implementation

[1]See some discussions of carbon leakage here: https://www.ft.com/content/ca51ebf5-fbb8-4c88-a93d-ded3d6d3bcdd and https://www.reuters.com/world/uk/uk-government-implement-carbon-levy-by-2027-2023-12-18/. While other fail to find a significant shift from domestic market to the globe (Duan et al. (2021)).

tax shock would increase the high-carbon imports by 1.5%

In addition, we confirm the relationship of carbon taxes is not solely at country level, but related to the fossil companies. By using global supplier chain of listed companies from 1980 to 2019, we show firms increase their suppliers (mostly foreign suppliers) after the carbon input cost at domestic markets. Most of foreign suppliers are producing the fossil products since domestic upper-stream customers faces a sudden strict environmental policy. Finally, we study the real effect of those foreign fossil suppliers. We find that after the introduction of a carbon tax in one market, fossil companies in foreign countries experience a real increase in their investment, sales growth, labor growth and innovation. This evidence is consistent with the idea that increased imports demands from domestic customers shift benefits to foreign suppliers in response to a tightening in domestic carbon pricing. These foreign fossil companies on the supply side will expand more on capital expenditure and grasp more opportunity to grow. Our results suggest that in addition to the carbon leakage effect, there are also real effects associations with the reallocation of international trade, contributing to uneven growth across geographic borders.

Our paper makes several contributions. Firstly, our paper is the very first to document the carbon leakage via international trade using a rich micro-level data(Schroeder and Stracca (2023), Laeven and Popov (2023)). Secondly, we related to a large broader literature of the climate change on the decision of firms (Patozi (2023)), but our focus is at cross-border spillovers of the climate risk. Thirdly, we contribute to understand global firm-to-firm supply chain, with a focus on the carbon transmission from upper-stream importers. (Mundaca et al. (2021), Berry et al. (2021)). Finally, we extend the literature on real corporate investment decision by documenting a cross-border learning effect. An implication for policy-makers is that cross-border learning by individual businesses can be important to understand multinationals, especially from China's rapidly growing manufacturing firms and the rest of the world.[2]

The rest of the paper is organized as follows. Section 2 outlines our testable hypotheses. Section 3 describes the data, construction of variables, and empirical methodology. Section 4 reports

[2]For example, Bailey et al. (2023), Autor et al. (2013) and Pierce and Schott (2016) study the cross-border peer effect of Chinese multinationals and US firms.

our main results. Section 5 concludes the paper.

2 Hypothesis Development

Most previous studies on the carbon taxes focus on domestic firm decision. Our priors is informed by theoretical work in which domestic firm can choose to import more ”dirty” products to where operations are affected by the introduction of a price of carbon.

On the domestic side, the reallocation of resources induced by a tighten carbon environment is very costly at domestic market or the market under the similar strict (environmental) regulation. It can lead a country to reduce its fossil consumption (Schroeder and Stracca (2023)). As a result, at least in a short-run, the carbon tax will force such domestic firms to cut their investment plan because it needs large upfront expenditure (Apicella and Fabiani (2023)). This in turn may lower the demands for carbon consumption at home [3]. Indeed, a country can also expect to import carbon intensive products from their fossil trade partner abroad. Based on these existing theories, we can form our following testable hypothesis:

H1: ***Carbon Leakage Hypothesis*** The introduction of carbon taxes in one country is associated with a decline of emission in that country but more imports of carbon products from other countries.

A country may further choose to import their products in countries with weak environmental standards to reduce its costs of pollution abatement. This pollution haven hypothesis has received substantial support from either FDI literature (Gu and Hale (2023)) or global outsourcing activity (Berry et al. (2021)), but little effect from international trade activity (Duan et al. (2021). It is hard to believe that international trade does not witness a production opportunity redistribution given the stringent environmental regulation at home. Carbon tax usually generate comparative disadvantage in producing carbon intensive goods and thus leak to carbon opportunity to foreign firms. It makes unilateral environmental policy less efficient in reducing global carbon emission, the main reason

[3] This evidence is not unambiguous. For example, Schroeder and Stracca (2023) find that carbon taxes reduce territorial emissions over time, but have no significant effect on consumption emissions.

that European Union calls for international cooperation and places tariffs on carbon imports to make a fair competition for domestic carbon producers and international suppliers.

There is also a growing debate on the credit reallocation from domestic credit market spillover to the foreign polluted countries with lax environmental regulation (Laeven and Popov, 2023, Ivanov et al., 2023). There could be a case that carbon producers are more likely to face financial constraint due to this credit misallocation shift to green financing. This reallocation can be viewed as the spillover of domestic carbon tax policy and contributing climate risks to the growth of emerging markets. Thus, we form our second testable hypothesis:

H2: ***Pollution Haven Hypothesis*** The introduction of carbon taxes in one country leads to more imports of carbon products from countries with weak environmental standards, or less developed markets.

If carbon emission can across the border, there will be an increasing (import) demand for fossil products via global firm-to-firm supply chain. The downstream customers grows to be green at the cost of their brown suppliers. A supplier aboard received carbon-intensive product order may expand its operating business in which we mean invest equipment or hire labors. If that is the case, this indirect trade channel will lead to the real impact of fossil firms aboard. Finally, we form our third testable hypothesis:

H3: ***Real Effect of Fossil Suppliers*** The introduction of carbon taxes in one country creates a real demand effect for foreign fossil suppliers. The affected suppliers will have a larger investment opportunity, and they are more likely to expand their operating business.

3 Data, Variable and Specification

3.1 Data

We combine data from several sources. For the annual country-level analyses, we rely mainly on the World Development Indicators (WDI) from the World Bank as it provides the most comprehensive coverage for cross country variables. Bilateral-product level trade data is from the

World Integrated Trade Solution (WITS) database. We obtain firm-level financial and stock data from Thomson Reuters Worldscope and Datastream respectively. Our global supply chain data is obtained from Factset Revere. We hand collected the implementation of carbon taxes for each country from Carbon Tax Center (http://www.carbontax.org/). The detailed information on data source is provided at Online Appendix Table A1.

3.1.1 Carbon Tax Data

We focus on the change of carbon taxes regulatory change based on the information from Carbon Tax Center. With the information of the size of tax, we only focus on the extensive marginal effect of the carbon tax. We also collected additional information of the time when a country choose to join an Emissions Trading Scheme (ETS) followed by Laeven and Popov (2023). As presented in Table 1, 25 (22) countries imposed some form of carbon tax (joined ETS) over year 1990 to 2020.

3.1.2 Country Level Data

We mainly use annual country-level data from the World Bank's World Development Indicators (WDI). This data set offers wide country coverage, containing the 195 countries (economies) listed in Table 1. The data set contains annual observations from 1960 to 2020. The WDI database is also useful in providing consistent coverage of many variables we use for cross sectional comparison. This includes key controls for our GDP growth and unemployment regressions such as trade to GDP, domestic credit to GDP, population, and GDP per capita. The aggregated environmental goods information are obtained from IMF climate change dashboard (https://climatedata.imf.org/).

3.1.3 Bilateral Trade Data

We also collect trade data from the World Integrated Trade Solution (WITS), which aggregates data from UN COMTRADE and UNCTAD TRAINS database. It provides bilateral trade exports and imports for more than 264 countries (economies) from 1995 to 2018. Besides, by using the

Table 1 Carbon Tax Schemes Included in the Sample

This table shows the carbon tax implementation year of the countries during our sample period (1990-2019).

Country	**Year CO_2 tax implemented**
Finland	1990
Poland	1990
Norway	1991
Sweden	1991
Denmark	1992
Slovenia	1996
Estonia	2000
Latvia	2004
Liechtenstein	2008
Switzerland	2008
Iceland	2010
Ireland	2010
Ukraine	2011
Japan	2012
United Kingdom	2013
France	2014
Mexico	2014
Spain	2014
Portugal	2015
Chile	2017
Colombia	2017
Argentina	2018
Canada	2019
Singapore	2019
South Africa	2019

advantage of product description at HS 6-digit, we identify the the high-carbon product to have the name of the following keywords: (1)cement (75 products), (2)iron and steel(312 products), (3) aluminium (34 products), fertilisers (26 products), (4) electricity (4 products) and (5) hydrogen (4 products). The detailed product information is obtained from Trade Statistics by Product (HS 6-digit) from WITS[4]. And those products are potential carbon leakage targeted by European countries[5]. The import of high-carbon products is aggregated at bilateral country level by year.

3.1.4 Firm Level Data

Firm-level financial information is gathered from Worldscope.We then exclude utilities (Standard Industrial Classification (SIC) codes 4900 -4999) and financial firms (SIC codes 6000-6999) since they are regulated. We further restrict the sample to firms located in countries with at least 10 publicly listed firms over the sample period. Our international firm-level sample consists of XX unique firms in XX countries for a total of XX firm-year observations. We define a fossil firm as its operation in SIC sectors 10xx, 12xx, 13xx, 14xx, 32xx, 33xx follows by Laeven and Popov (2023).[6]. The detailed firm level variable construction can be found at Table A1. We winsor all firm-level continuous measures at top and bottom 1%.

The global supply chain information is systematically collected from Factset Revere dataset, as it is designed to uncover firm-to-firm business relationship interconnections globally. The Revere provides four normalized relationship types: (i) customers, (ii) suppliers, (iii) competitors, and (iv) strategic partners. We identify a firm's supplier and customer firms using relationship types categorized as 'suppliers' and 'customers'. The FactSet Revere supply chain relationship database covers approximately 200,000 firms, including more than 30,000 publicly listed firms around the world, comprising over 725,000 unique business relationships, with historical data going back as far as 2003. Importantly, the FactSet Revere database includes both publicly listed and private

[4]See: https://wits.worldbank.org/trade/country-byhs6product.aspx?lang=en.

[5]See media reports for details: Carbon Border Adjustment Mechanism, https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en.

[6]We further test the fossil firms in a relatively narrowed fossil industries such as 12xx, 13xx. The results remain unchanged.

firms, provides both important and less important relationships, and incorporates relationship information obtained from both the direct disclosure of a source company and the reverse disclosure of another company regarding the source company. For our study, we only limit information to the publicly traded firm as we need their operation performance as well as their fossil business. Our final sample of 95,665 unique firms, from 120 countries/economies over 2003 and 2021.

3.1.5 Variable Construction, Summary Statistics and Correlation

All continuous variables are winsored at the top and bottom 1% to remove outliers. Variable construction are in Table A1 of our online appendix. Table 2 presents the descriptive statistics of all key variables at country level, bilateral-country level, product level, firm level. And before we turn to a multivariate econometric analysis, it is instructive to show some basic correlation between fossil imports and carbon taxes.

3.2 Regression Specification

3.2.1 Country level

In order to explore the impact of the domestic carbon tax on CO_2 emissions and high-carbon imports, we set the following regressions:

$$Y_{ct} = \alpha + \beta * Carbontaxshock_{ct} + Z_{ct} + \mu_c + \theta_t + \varepsilon_{ct} \tag{1}$$

where c is the country, t is year. Y_{ct} is the country-level outcomes, including the CO_2 emissions and the high-carbon product imports. $Carbontaxshock_{ct}$ is a dummy variable defined to be 1 after a country has implemented the carbon tax. Z_{ct} are a series of country-level control variables, including GDP, GDP per capita, inflation level and real exchange rate fluctuation.μ_c is the country fixed effect, and θ_t is year fixed effect. Standard errors are clustered at country-year level.

Table 2 Descriptive Statistics

This table reports descriptive statistics for annual country-level, bilateral-level, country-product-level data over period 1995 to 2018. Our firm-level data is available from 1980 to 2022. Variables are defined in Appendix A1. Panel A presents summary statistics for key variables used in our country-level baseline regression. Panel B presents summary statistics of bilateral country level information. Panel C presents summary statistics of product-country level (HS 6-digit code) estimation. Panel D reports the summary statistics for key variables for listed firms and merged with their supply chain information.

	(1)	(2)	(3)	(4)	(5)	(6)
Variable	Obs	Mean	Std. Dev.	p25	p50	p75
Panel A: Country-level data						
Carbon tax shock	5460	0.060	0.238	0.000	0.000	0.000
CO2 emission per GDP	4808	0.526	0.531	0.239	0.351	0.606
High-carbon import (billion USD)	4559	5.533	15.748	0.083	0.511	3.003
ln(GDP per capita)	5290	8.305	1.430	7.066	8.292	9.628
ln(GDP)	5287	23.800	2.393	22.148	23.620	25.550
ln(CPI)	4771	4.415	0.750	4.265	4.546	4.717
ln(REER)	2596	4.598	0.194	4.530	4.603	4.668
Panel B: Country-product level data						
ln (Product imports)	18714494	12.377	3.407	10.022	12.417	14.802
Carbon tax shock	18714513	0.066	0.249	0.000	0.000	0.000
High-carbon product dummy	18714513	0.071	0.256	0.000	0.000	0.000
ln(GDP per capita)	17203481	8.534	1.556	7.309	8.552	9.874
ln(GDP)	17203481	24.348	2.283	22.762	24.253	26.033
Panel C: Bilateral-level data						
ln(High-carbon product imports)	291019	13.156	3.897	10.553	13.339	15.987
Carbon tax shock domestic	291019	0.058	0.234	0.000	0.000	0.000
ln(GDP per capita domestic)	266090	8.808	1.431	7.661	8.784	10.195
ln(GDP domestic)	269889	24.681	2.256	23.014	24.650	26.410
Carbon tax shock foreign	291019	0.124	0.302	0.000	0.000	0.000
ln(GDP per capita foreign)	277876	9.285	1.260	8.305	9.397	10.470
ln(GDP foreign)	279637	25.737	1.929	24.346	25.945	27.029
Panel D: Firm-level data						
#Supplier	685879	0.643	3.699	0.000	0.000	0.000
#Foreign supplier	685879	0.384	2.623	0.000	0.000	0.000
#Domestic supplier	685879	0.258	1.763	0.000	0.000	0.000
#Fossil supplier	685879	0.026	0.325	0.000	0.000	0.000
#Foreign fossil supplier	685879	0.014	0.219	0.000	0.000	0.000
#Domestic fossil supplier	685879	0.012	0.180	0.000	0.000	0.000
Carbon tax shock	685879	0.125	0.331	0.000	0.000	0.000
Home carbon tax shock	683680	0.095	0.294	0.000	0.000	0.000
Number of home carbon tax shock	685879	0.416	4.847	0.000	0.000	0.000
ln(Assets)	685879	20.849	3.268	18.506	20.841	22.998
Leverage	638918	0.249	0.266	0.030	0.190	0.376
Cash	638518	0.234	0.326	0.048	0.130	0.289
CAPEX	624752	0.059	0.089	0.010	0.029	0.069
ROA	636773	-0.032	0.282	-0.033	0.027	0.076
ROE	637967	-0.007	0.510	-0.032	0.064	0.149
Tobin Q	583564	1.808	1.610	0.935	1.261	2.000
Staff cost	391547	0.387	1.333	0.065	0.136	0.272
PPENT	631897	0.331	0.284	0.101	0.267	0.487
Cash flow	495695	0.069	0.126	0.027	0.072	0.127
EBIT	614752	0.005	0.267	-0.014	0.052	0.113
Fossil	685879	0.140	0.347	0.000	0.000	0.000

3.2.2 Product level

To further compare the impact of carbon tax shock on the imports of high-carbon products with the impact on other products, we use the more dis-aggregated country-product level data to run regressions. The product-level specification is as follows:

$$
\begin{aligned}
ln(Prod.Imp._{cpt}) = \alpha + \beta_1 * Carbontaxshock_{ct} + \beta_2 * Carbontaxshock_{ct} * High-carbon_p \\
+ Z_{ct} + \mu_{cp} + \theta_t + \varepsilon_{cpt}
\end{aligned}
\tag{2}
$$

where c is the importing country, p is the product (HS-6 digit).$Prod.Imp._{cpt}$ is the import value of country c, for product p in year t. $High-carbon_p$ is the high-carbon product dummy, which is set to be 1 for high-carbon products. $\mu_c p$ is the country-product fixed effect, and θ_t is year fixed effect. For robustness checks, we also employ stricter country-year fixed effects to absorb the impact of all the country-level time-varying shocks. Standard errors are clustered at country-year level. We mainly focus on the coefficient β_2, which demonstrates the heterogeneous impact of the carbon tax shock on high-carbon goods and other products.

3.2.3 Bilateral level

To test the pollution haven hypothesis, we construct the following bilateral level regressions:

$$
\begin{aligned}
ln(High-carbonimports_{ijt}) = \alpha + \beta_1 * Carbontaxshock_{it} + \beta_2 * Carbontaxshock_{it} * X_j \\
+ Z_{ijt} + \mu_{ij} + \theta_t + \varepsilon_{ijt}
\end{aligned}
\tag{3}
$$

where i and j are importing country and exporting country, respectively. $High-carbonimports_{ijt}$ refers to the high-carbon import value of i from country j in year t. X_j refers to a series of exporting country's characteristics, including whether it belongs to the high-carbon emission economies, or if it is U.S./China. Z_{ijt} are a series of importing countries' or exporting countries' control variables, including GDP and GDP per capita. μ_{ij} is the country-pair fixed effect. Standard errors are clustered at country-pair level.

3.2.4 Firm level

In order to test the real effect hypothesis, we use the firm-level data with global supply chain information.

Firstly, to explore whether the domestic carbon shock would promote the global supply chain, we set the following regressions.

$$SupplierNumber_{fct} = \alpha + \beta * Carbontaxshock_{ct} + Z_{ft} + \mu_f + \theta_t + \varepsilon_{fct} \tag{4}$$

where f represents firm, c is the country where the firm is located. Z_{ft} are a series of firm-level control variables, including the firm assets, leverage, cash ratio, capital expenditure, return on assets, return on equity, Tobin Q, staff costs, fixed investment (PPENT), cash flow and EBIT. μ_f is firm fixed effect. Standard errors are clustered at firm level.

Secondly, we aim to test the real effect hypothesis, that the carbon tax shock to the customer would have a spillover effect on the performance of suppliers. We set the following regression:

$$SupplierPerformance_{st} = \alpha + \beta * HomeCarbontaxshock_{ct} + Z_{st} + \mu_s + \theta_t + \varepsilon_{st} \tag{5}$$

where s is the supplier, $HomeCarbontaxshock$ shows whether the country where the supplier's customers are located has implemented the carbon tax. If at least one of the customer's country has implemented the carbon tax, the $HomeCarbontaxshock$ dummy is set to be 1. Z_{st} are a series of suppliers' control variables, including the firm assets, leverage, Tobin Q, cash flow and EBIT. ε_{st} is the supplier fixed effect. The coefficient β captures whether the carbon tax shock in the customers' country would have a significant impact on the performance of upstream suppliers.

4 Empirical Evidence

4.1 Country-level Evidence

In table 3, we directly test hypothesis 1, carbon leakage hypothesis, using the country-level data. All regressions include the firm fixed effects and the year dummies. In columns (1) through (3), we firstly explore the impact of the carbon tax shock on the CO_2 emission level (kg per 2015 US$ of GDP). Column (1) presents the baseline estimates. The coefficient for the carbon tax shock is significantly negative, implying that the implementation of the carbon tax would significantly reduce the CO_2 level. This result indicates that the carbon taxes are quite useful in reducing domestic (territorial) CO_2 emissions, which is consistent with Schroeder and Stracca (2023). In the baseline regression, we control factors such as domestic total demand (GDP) and economic development (GDP per capita). Column (2) and (3) consider other factors that may affect the country CO_2 emissions and international trade. Column (2) controls for the domestic price variation, using the CPI index as the measure. We find that the increase of domestic price level would decrease the CO_2 emissions. Column (3) further incorporates the influence of the exchange rate fluctuation. We use the real effective exchange rate index to represent the exchange rate shock faced by each country. The main result remains robust after we consider more macro factors. The economic magnitude of this carbon tax is sizable: a country which introduced carbon tax is associated with a 15.3% average decrease in a typical country's domestic CO_2 emission as a fraction of its GDP (in 2015 US dollar).[7]

To directly test the carbon leakage hypothesis, Columns (4) to (6) demonstrate the impact of the the tax carbon shock on the high-carbon product imports. Column (4) shows the baseline result. The coefficient of the carbon tax shock is significant and positive, indicating that the implementation of the carbon tax would increase the high-carbon imports of the country. This result is in line with the carbon-leakage hypothesis. Columns (5) and (6) show the results when considering other factors. Our results remain robust. To reduce the domestic CO_2 emissions, countries with car-

[7] $0.153 = 0.081 \div 0.526$. Given the average of country-level carbon emission at Table 2.

bon taxes would decrease the domestic production of high-carbon products and import more from other countries, leading to the carbon leakage. The magnitude of carbon leakage is about 24.0% [8] Schroeder and Stracca (2023) finds that carbon taxes reduce territorial emissions over time, but have no significant effect on consumption emissions. Our results in table 3 further confirm the idea by providing carbon leakage evidence from the perspective of high-carbon trade.

Table 3 Domestic carbon taxes and international imports: country-level result

This table reports country-level estimation after the introduction of domestic carbon taxes from year 1995 to 2018. The dependent variable is country-level carbon emission (Column 1 to 3), and high-carbon imports in billion dollar amount (Column 4 to 6). The key interest independent variable is carbon tax shock, which equals to one if a domestic country introduced carbon tax at given year onwards. We add other country level controls and fixed effects as specified. Standard errors clustered at the country-year level appear in the parentheses, where ***, ** and * indicate significance at the 1%, 5% and 10% levels respectively.

	(1)	(2)	(3)	(4)	(5)	(6)
		CO_2 kg per GDP			High carbon imports (in billion dollar)	
Carbon tax shock	-0.104***	-0.127***	-0.081***	7.707***	6.101***	3.160*
	(0.028)	(0.028)	(0.026)	(1.734)	(1.749)	(1.904)
ln(GDP per capita)	-0.658***	-0.726***	-0.865***	12.834***	16.920***	24.896***
	(0.042)	(0.047)	(0.070)	(1.429)	(1.525)	(2.700)
ln(GDP)	0.458***	0.556***	0.720***	-15.385***	-19.844***	-31.020***
	(0.038)	(0.044)	(0.065)	(1.510)	(1.607)	(2.750)
ln(CPI)		-0.063***	-0.071***		-1.831***	-3.606***
		(0.013)	(0.018)		(0.416)	(0.888)
ln(Exchange rate)			-0.004			2.073
			(0.037)			(1.445)
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	4,803	4,446	2,427	4,451	4,048	2,178
Adjusted R^2	0.868	0.883	0.918	0.706	0.716	0.729

4.2 Product-level Evidence

The previous analysis of carbon leakage was primarily based on country-level data. In this section, we will further utilize more granular country-product level data to provide additional evidence for carbon leakage. Specifically, we collect import data at the HS-6 digit product level for all countries in our sample. By breaking down the data to the product level, we can examine whether there is

[8] 0.24 = 3.16 billion *div* 13.156 billion. Given the average bilateral carbon imports at Table 2.

a significant difference in the import value of high-carbon products compared to other products when a country implements the carbon tax.

Table 4 presents the regression results at the product level. In column (1), we examine the heterogeneity in the impact of carbon tax shock on the import values of high-carbon products and other products. To control for inherent country preferences for specific products, we include country-product level fixed effects. Year dummies are also used to absorb the effects of macroeconomic shocks. Column (1) shows that the coefficient of the carbon tax shock is significantly negative, yet the interaction term between carbon tax shock and the high-carbon product dummy variable is significantly positive. This suggests that after a country implements the carbon tax, the import value of high-carbon products increases significantly, while the import value of other products decreases to some extent. This result further supports the carbon leakage hypothesis. In column (1), to control for country-level factors' interference with the results, we include country-level GDP and per capita GDP indicators. In column (2), to further eliminate the potential impact of time-varying factors at the country level, we include country-year fixed effects. The results show that the country-year fixed effects absorb all country-level factors, including the impact of carbon tax shock. However, even after adopting more stringent fixed effects, the interaction term between carbon tax shock and the high-carbon product dummy variable remains significantly positive. For the economic magnitude, a country generally will import 1.57% [9] additional carbon goods (Column 2) after the carbon tax implementation.

To further validate the robustness of the results, in columns (3)-(6), we use the ratio of product import value to GDP and the ratio of product import value to the country's total import value as dependent variables, respectively, and reanalyze the data. The results show that even with alternative dependent variables, the conclusion of this study remains robust, indicating that the implementation of the carbon tax in a country significantly increases the import of high-carbon products. Table 4 provides empirical evidence at the product level for the carbon leakage hypothesis.

[9] 1.57% = 0.188/13.156

Table 4 Domestic carbon taxes and international imports: product-level result

This table reports country-product level estimation after the introduction of domestic carbon taxes from year 1995 to 2018. The dependent variable is product-level import value (in logs, Column 1 and 2), the ratio of product import value to country GDP, and the ratio of product import value to the country's total imports (Column 5 and 6). The key interest independent variable is carbon tax shock, which equals to one if a domestic country introduced carbon tax at given year onwards. We add other country level controls and fixed effects as specified. Standard errors clustered at the country-year level appear in the parentheses, where ***, ** and * indicate significance at the 1%, 5% and 10% levels respectively.

	(1)	(2)	(3)	(4)	(5)	(6)
	ln(Prod.imports)		Prod.imports/GDP		Prod.imports/Total imports	
Carbon tax shock×High carbon product	0.187***	0.188***	0.008***	0.008***	0.022***	0.021***
	(0.019)	(0.019)	(0.002)	(0.001)	(0.005)	(0.003)
Carbon tax shock	-0.058**		-0.007***		-0.017***	
	(0.026)		(0.003)		(0.006)	
ln(GDP)	0.355***		-0.077***		-0.159***	
	(0.053)		(0.005)		(0.012)	
ln(GDP per capita)	0.427***		0.060***		0.159***	
	(0.058)		(0.005)		(0.013)	
Country-product FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	No	Yes	No	Yes	No
Country-year FE	No	Yes	No	Yes	No	Yes
Observations	17,123,816	18,587,012	17,123,832	17,123,832	15,301,286	15,323,444
Adjusted R^2	0.806	0.814	0.690	0.699	0.707	0.712

4.3 Bilateral-level Evidence

In the country-level analysis, we find that the imposition of carbon taxes significantly reduces the CO_2 emissions of the country and substantially increases the import of high-carbon products, leading to the frequently mentioned phenomenon of carbon leakage in news reports. The next interesting question is, from which economies do the countries implementing carbon taxes primarily import high-carbon products? According to Hypothesis 2, these high-carbon products mainly originate from countries with weaker environmental regulations or less developed countries, namely the Pollution Haven Hypothesis. Using only country-level data is insufficient to test this Pollution Haven Hypothesis. Therefore, we further utilize the bilateral high-carbon product trade data to analyze the impact of exporter heterogeneity on our baseline result. Table 5 presents the regression results using bilateral trade data. In all regressions, we control for country-pair fixed effects, year dummies, as well as the GDP and GDP per capita levels of both the home country (importer) and the foreign country (exporter).

Column (1) indicates that the coefficient of the (domestic) carbon tax shock is significantly positive, suggesting that when a country implements the carbon tax, the high-carbon imports from other countries would significantly increase. This result is consistent with the result in Table 3. Based on column (1), Column (2) further introduces a dummy variable indicating whether the foreign country (exporter) also implements the carbon tax. The results show that the coefficient of the domestic carbon tax shock remains significantly positive, while the coefficient of the foreign carbon tax shock is significantly negative, and the magnitudes of the coefficients for domestic and foreign carbon tax shock dummies are relatively similar. This result demonstrates that countries implementing carbon taxes primarily import high-carbon products from economies without carbon taxes.

China and the United States together emit more than 40 percent of the world's carbon dioxide (CO2), and neither of them has implemented carbon taxes. So, for countries implementing carbon taxes, are China and the U.S. the main source countries for high-carbon products? To analyze this question, we construct dummy variables for both China and the U.S as exporters. If the exporter is China (U.S.), the dummy variable $Exporter = China(US)$ takes the value of 1; otherwise, it takes the value of 0. Subsequently, we construct the interaction terms between the domestic carbon tax shock and the China/U.S. dummy variables and add them to the baseline regression. Column (3) shows that the interaction term between carbon tax shock and the U.S. dummy variable is not significant, while the interaction term between carbon tax shock and the China dummy variable is significantly positive. Meanwhile, the coefficient of the carbon tax shock remains significantly positive. The results in column (3) indicate that China is one of the main countries for carbon leakage, being the primary supplier of high-carbon products imported by countries implementing carbon taxes. However, there is no clear evidence that the U.S. has been significantly affected by carbon leakage.

Column (4) further examines the impact of carbon emissions or environmental regulation heterogeneity on the effect of carbon tax shock. Specifically, based on the average carbon emissions of each country during the sample period, we classify all countries into high-emission economies and low-emission economies. We then add the interaction term between carbon tax shock and high-carbon emission exporter dummy into the baseline regression. The result shows that the interaction term carbon emission countries and low-carbon emission countries. If the average carbon emission of one exporter is above the median level of all countries, the country would be classified as high-carbon emission exporter, and the high-carbon emission exporter dummy is set to between carbon tax shock and high-carbon emission is significantly positive, indicating that after the implementation of carbon taxes, countries mainly import high-carbon products from exporters with high carbon emissions or weaker environmental regulations, confirming the second hypothesis, i.e., the Pollution Haven Hypothesis. Based on column (4) of Table 5, When a country enforced a carbon tax, high-carbon imports from high-carbon-emission countries will increase by 1.5% [10]

4.4 Firm-level Evidence

To validate Hypothesis 3, we conduct further analysis using more granular firm-level data. The Factset Revere dataset provides information on global firm-to-firm supply relationships, enabling us not only to examine the impact of carbon tax shock on domestic firms, but also to investigate the spillover effects of the carbon tax shock on upstream suppliers along the global supply chain.

Based on the previous analysis, we anticipate a significant increase in the import of high-carbon products after the implementation of carbon taxes by a country. At the micro firm level, we expect to observe an increase in the number of foreign suppliers, especially those fossil suppliers. This phenomenon is also expected to be more pronounced in the fossil industry. Table 6 presents the regression results at the firm level. In all regressions, we control for firm-fixed effects and year dummies. Column (1) demonstrates the impact of carbon tax shock on the number of suppliers for domestic firms. The results indicate a significantly positive coefficient for the carbon tax shock, suggesting that the implementation of carbon taxes substantially increases the number of suppliers. Columns (2) and (3) respectively show changes in the number of foreign and domestic suppliers. Economically, based on the results of columns (1) to (3), the introduction of the carbon tax shock

[10] $1.5\% = 0.207 \div 13.156$.

Table 5 Domestic carbon taxes and international imports: bilateral-country result

This table reports bilateral-country level estimation after the introduction of domestic carbon taxes from year 1995 to 2018. The dependent variable is high-carbon product imports in **logs** dollar amount between *domestic* country (importer) and *foreign* country (exporter) at a given year. The *Carbon Tax Shock Domestic* is defined as *domestic* carbon tax shock, which equals to one if a domestic country introduced carbon tax at given year onwards. The *Carbon Tax Shock Foreign* is defined as *foreign* carbon tax shock, which equals to one if the *foreign* country introduced carbon tax at given year onwards. We add other domestic and foreign country level controls and fixed effects as specified. Standard errors clustered at the country-pair level appear in the parentheses, where ***, ** and * indicate significance at the 1%, 5% and 10% levels respectively.

	(1)	(2)	(3)	(4)
	ln (High-carbon imports)			
Carbon tax shock domestic	0.137***	0.136***	0.128**	0.026
	(0.050)	(0.050)	(0.051)	(0.067)
Carbon tax shock foreign		-0.133***		
		(0.045)		
Carbon tax shock domestic × Exporter=US			-0.223	
			(0.157)	
Carbon tax shock domestic × Exporter=China			0.869**	
			(0.362)	
Carbon tax shock domestic × High carbon emission				0.207**
				(0.097)
ln(GDP domestic)	0.527***	0.526***	0.526***	0.526***
	(0.033)	(0.033)	(0.033)	(0.033)
ln(GDP per capita domestic)	0.613***	0.615***	0.613***	0.614***
	(0.063)	(0.063)	(0.063)	(0.063)
ln(GDP foreign)	-0.109**	-0.129***	-0.110**	-0.111**
	(0.047)	(0.047)	(0.047)	(0.047)
ln(GDP per capita foreign)	1.267***	1.278***	1.257***	1.261***
	(0.089)	(0.089)	(0.089)	(0.089)
Country pair FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	251136	251136	251136	251136
Adjusted R^2	0.789	0.789	0.789	0.789

would averagely increase the number of suppliers, number of foreign suppliers by 51% and 127% [11] respectively. Meanwhile, the number of domestic suppliers would decrease by 61% [12]. The results reveal that carbon tax implementation significantly increases the number of foreign suppliers while decreasing the number of domestic suppliers. These results suggest that the carbon tax would enhance the global sourcing.

In Column (4), we focus on fossil suppliers, introducing an interaction term between the carbon tax shock and a fossil industry dummy variable. The results show a significantly positive coefficient for the interaction term, indicating that carbon tax implementation leads to domestic fossil firms having more fossil suppliers. Columns (5) and (6) further decompose fossil suppliers into foreign and domestic categories, showing that the increase in fossil suppliers is mainly driven by an increase in foreign fossil suppliers. Economically speaking, compared to the firms in other industries, the number of fossil suppliers and foreign fossil suppliers of firms in fossil industry would increase by 11.3% [13] and 0.045 [14], respectively.

4.5 Real Effect

Table 7 demonstrates the spillover effects of carbon tax implementation on upstream supplier firms through the global supply chain. According to Hypothesis 3, the implementation of carbon taxes increases the real demand for foreign upstream fossil suppliers, leading to their production expansion. Therefore, we expect a positive impact of carbon tax implementation on the performance of upstream fossil suppliers. Table 7 reports the results of spillover effects. In contrast to Table 6, this table focuses on suppliers, examining the impact of carbon tax implementation in the country where downstream customers are located on the performance of suppliers. The variable "Home carbon tax shock" is used to measure whether the the country of its customer has implemented carbon tax. If at least on of the countries (where the customers are located) has implemented a car-

[11] 51% = 0.233÷0.453 and =0.345÷0.271
[12] 61% = 0.112/0.182
[13] 11.3%= 0.051 ÷0.453
[14] 16.7%= 0.045 ÷0.271

Table 6 Domestic carbon taxes and international imports: firm-level result

This table reports firm-level estimation after the introduction of domestic carbon taxes from year 1980 to 2020. The dependent variable is number of supplier, number of foreign supplier and number of domestic foreign supplier for column (1) to column (3), respectively. We further identify whether those suppliers belong to the fossil sectors (SIC codes: 12xx, 13xx, 10xx,14xx, 32xx,33xx). The key interest independent variable is carbon tax shock, which equals to one if a domestic country introduced carbon tax at given year onwards. Fossil is a dummy variable equals to one if a firm operated in fossil sectors. We add other firm level controls and fixed effects as specified. Standard errors clustered at firm level appear in the parentheses, where ***, ** and * indicate significance at the 1%, 5% and 10% levels respectively.

	(1)	(2)	(3)	(4)	(5)	(6)
	#Supplier	#Fsupplier	#Dsupplier	#Fossil supplier	#Fossil Fsupplier	#Fossil Dsupplier
Carbon tax shock	0.342***	0.448***	-0.106***	-0.037**	-0.013	-0.023***
	(0.118)	(0.103)	(0.025)	(0.015)	(0.009)	(0.009)
Carbon tax shock × Fossil				0.073***	0.063***	0.010
				(0.018)	(0.018)	(0.009)
ln(Assets)	0.196***	0.182***	0.014	-0.003	-0.001	-0.002
	(0.035)	(0.030)	(0.009)	(0.006)	(0.003)	(0.004)
Leverage	0.048	0.036	0.011	-0.002	-0.002	-0.000
	(0.067)	(0.057)	(0.022)	(0.005)	(0.004)	(0.002)
Cash	-0.192***	-0.142***	-0.051***	0.002	-0.002	0.004
	(0.052)	(0.042)	(0.019)	(0.005)	(0.003)	(0.004)
CAPEX	0.395***	0.282***	0.112***	-0.006	0.002	-0.008
	(0.106)	(0.083)	(0.041)	(0.011)	(0.007)	(0.007)
ROA	-1.209***	-1.091***	-0.118	-0.026	-0.024	-0.002
	(0.273)	(0.229)	(0.086)	(0.022)	(0.019)	(0.008)
Tobin Q	0.013	0.013	0.000	-0.002	-0.002**	-0.001
	(0.011)	(0.009)	(0.004)	(0.002)	(0.001)	(0.001)
Staff cost	-0.011	-0.009	-0.003	-0.001	-0.001**	0.000
	(0.008)	(0.007)	(0.003)	(0.001)	(0.001)	(0.001)
Cash flow	1.133***	0.973***	0.159*	0.040	0.028	0.011
	(0.272)	(0.227)	(0.087)	(0.028)	(0.021)	(0.010)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	285679	285679	285679	285679	285679	285679
Adjusted R^2	0.418	0.405	0.417	0.463	0.432	0.457

bon tax, the variable takes the value of 1. "Fossil" represents whether the supplier is in the fossil industry. The results show that the coefficients of Home carbon tax shock and the fossil industry dummy variable are significantly positive for all regressions, except for leverage. This indicates that the implementation of carbon taxes in the country of downstream firms significantly improves the performance of upstream suppliers, including increased employment, sales, cash, profits and decreased leverage, and this phenomenon is concentrated in the fossil industry.

Table 7 Domestic carbon taxes and international imports: real effects

This table reports foreign firm-level outcome after the introduction of domestic carbon taxes from year 1980 to 2020. The dependent variable is labor in logarithm (column 1), sale in logarithm (column 2), cash to assets (times 100, column 3), ROA (times 100, column 4), debt to assets (times 100, column 5). The key interest independent variable is home carbon tax shock, which equals to one if a domestic country where the downstream customer headquartered introduced carbon tax at given year onwards. Fossil is a dummy variable equals to one if the supplier operated in fossil sectors(SIC codes: 12xx, 13xx, 10xx,14xx, 32xx,33xx). We add other firm level controls and fixed effects as specified. Standard errors clustered at the firm level appear in the parentheses, where ***, ** and * indicate significance at the 1%, 5% and 10% levels respectively.

	(1) ln(Labor)	(2) ln(Sales)	(3) Cash/Asset	(4) ROA	(5) Leverage
Home carbon tax shock	-0.004	0.033***	-0.217**	-0.044**	-0.177
	(0.028)	(0.006)	(0.099)	(0.019)	(0.163)
Home carbon tax shock × Fossil	0.310***	0.059**	0.487**	0.134**	-1.091**
	(0.087)	(0.028)	(0.228)	(0.055)	(0.479)
ln(Assets)	0.857***	0.917***	-0.327***	0.141***	6.809***
	(0.014)	(0.009)	(0.082)	(0.019)	(0.129)
Tobin Q	0.067***	0.007*	2.069***	0.039***	0.242***
	(0.005)	(0.004)	(0.056)	(0.010)	(0.058)
Cash flow	0.041	1.130***	34.098***	94.126***	-9.160***
	(0.045)	(0.036)	(0.535)	(0.126)	(0.542)
Firm FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Observations	440561	440440	437538	440278	438437
Adjusted R^2	0.721	0.942	0.511	0.932	0.577

5 Conclusion

In this paper, based on the country-level, product-level and firm-level data, we find robust evidence of production leakage of environmental policies. When faced with the carbon tax shock, affected counties would significantly reduce the CO_2 emissions, yet at the same time they would also import more carbon products. Bilateral evidence further indicates that the high-carbon products mainly come from the high emission countries, or the countries with less strict environmental regulations. Firm-level evidence demonstrates that the implementation of the domestic carbon tax shock would boost the global supply chain relationship by increasing the number of suppliers, especially the fossil suppliers from foreign countries. Finally, we also find robust spillover effect of the environmental policy. The implementation of the carbon tax shock in the downstream country would have a strong promoting effect on the performance of upstream suppliers, and this effects are also concentrated in suppliers at fossil industries.

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Internet Appendix

Production Leakage: Evidence from Uncoordinated Environmental Policies

(Intended for online publication only)

by Z. Li, and B. Lu, and S. Zhou

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Table A1 Variable Definitions

This table reports definitions for our variables and data sources for empirical tests.

Variable	Description	Source
Carbon Related Measures		
Carbon Tax Shock	An indicator equals to one if a country implemented carbon tax after year t and zero otherwise.	Hand Collected
Carbon Tax Shock Domestic	An indicator equals to one if a domestic country (importer country) implemented carbon tax after year t and zero otherwise.	Hand Collected
Carbon Tax Shock Foreign	An indicator equals to one if a foreign country (exporter country) implemented carbon tax after year t and zero otherwise.	Hand Collected
ETS Shock	An indicator equals to one if a country joined an Emissions Trading Scheme (ETS) after year t and zero otherwise.	Hand Collected
Country Level Measures		
CO2 Emission per GDP	CO2 emissions per unit of GDP are expressed in kilogrammes of CO_2 per 2015 USD of GDP.	WDI
High-carbon Import	Aggregation of high-carbon imports in billion based on HS 6-digit level.	WITS
Ln(GDP per capita)	The natural logarithm of GDP per capita (measured as GDP divided by midyear population) in constant 2010 U.S. dollar at year t.	WDI
Ln(GDP)	The natural logarithm of GDP in current U.S. dollar at year t.	WDI
Ln(CPI)	The natural logarithm of Consumer Price Index (CPI) at year t.	WDI
Ln(REER)	The natural logarithm of real effective exchange rate index at year t	WDI
Product Level Measures		
Ln(Prod Imports)	The natural logarithm of import value in US dollar at year t	WITS
Prod. Imports/GDP	The value of product imports divided by current GDP at year t	WITS,WDI
Prod. Imports/Total Imports	The value of product imports divided by the total value of imports at year t	WITS

Variable	Description	Source
Firm Level Measures		
Ln(Assets)	Logarithmic value of total assets(Worldscope item02999)	Worldscope
Leverage	Total debt (Worldscope item 03255) divided by assets (Worldscope item 02999).	Worldscope
Cash	Cash holdings (Worldscope item 02001) divided by assets (Worldscope item 02999).	Worldscope
CAPEX	Capital expenditures (Worldscope item 04601) divided by assets (Worldscope item 02999).	Worldscope
ROA	Net income (Worldscope item 01751) scaled by total assets (Worldscope item 02999)	Worldscope
ROE	Net income (Worldscope item 01751) scaled by shareholder equity (Worldscope item 03451+Worldscope item 03501).	Worldscope
Tobin's Q	Assets (Worldscope item 02999) plus market value of equity (Worldscope item 08001) minus book value of equity (Worldscope item 03501) divided by total assets.	Worldscope
Staff Cost	Wages paid to employees (Worldscope item 01084) divided by sales.	Worldscope
PPENT	Net property, plant, and equipment (Worldscope item 02501) divided by assets (Worldscope item 02999).	Worldscope
Cash Flow	Earnings before Interest, Taxes, Depreciation & Amortization (EBITDA) (Worldscope item 18198) minus interest-bearing debt (Worldscope item 01251) minus taxes (Worldscope item 01451) divided by total assets (Worldscope item 02999).	Worldscope
EBIT	Earnings before Interest, Taxes, Depreciation & Amortization (EBITDA) (Worldscope item 18198) divided by total assets (Worldscope item 02999).	Worldscope