Production Leakage: Evidence from Uncoordinated Environmental Policies

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- **Carbon/Production Leakage**: national carbon policy fails to drive down global carbon emission? Global CO_2 Emission
- What are the effects of **Production Leakage** via global supply chain?

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- **Pecuniary externality** Uneven distribution of production opportunity created arbitrage on international carbon trade
- Pollution haven countries produced more carbon-intensive goods.
- Environmental policy coordination is important. (Green your country versus Green the planet).

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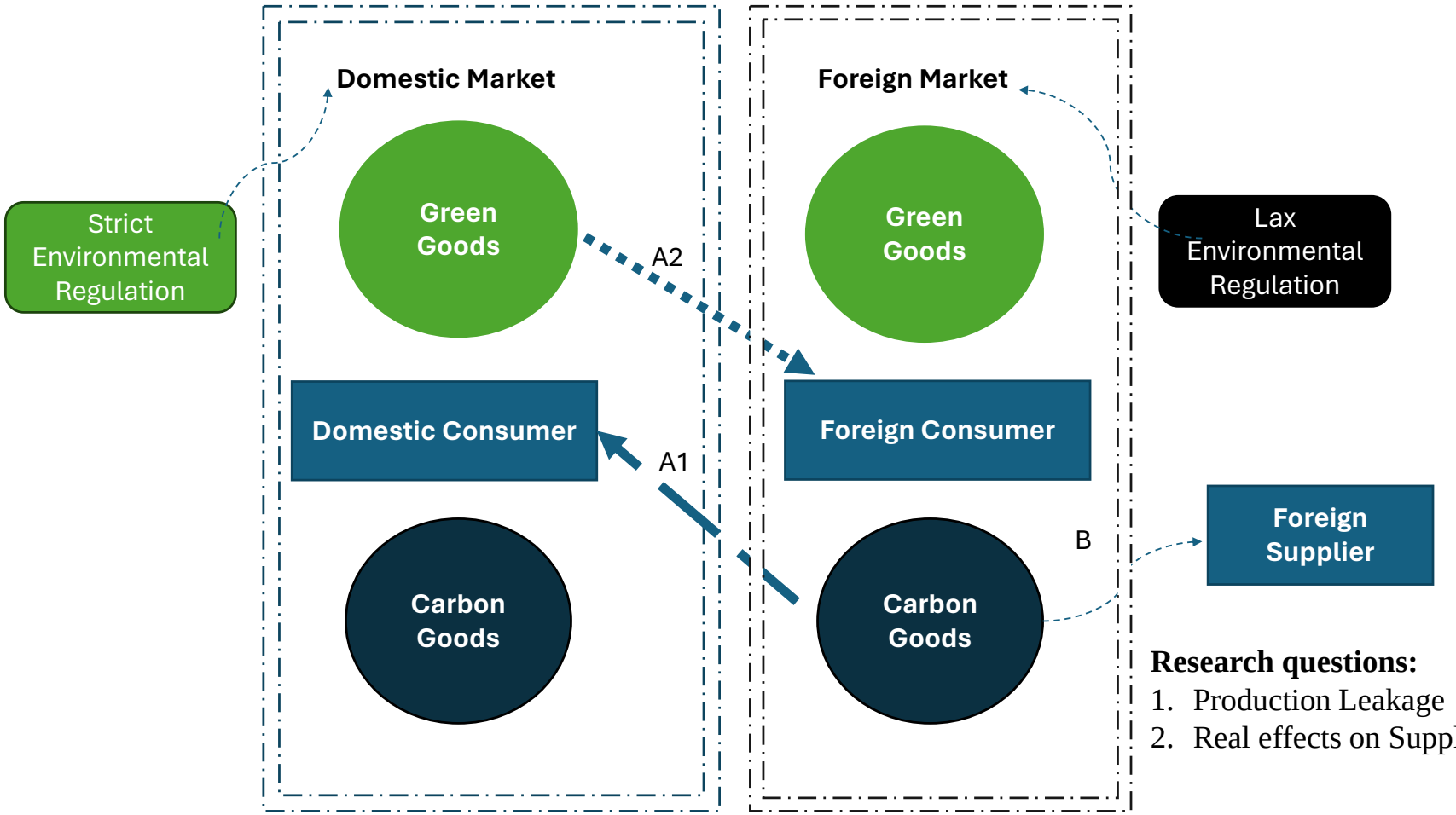
What we do

- Provide a simple model to justify the carbon leakage on international trade.
- Test if the data can replicate the findings of the model.
- Use carbon tax, emission trading scheme (ETS), carbon tax price as shocks.

Framework of our story



Research questions:

1. Production Leakage
2. Real effects on Supplier

Why carbon leakage is hard to stop

Trade policies such as cross-border carbon taxes are designed to prevent the carbon leakage, but their effects are not clear.

- In May 2023, the EU's Carbon Border Adjustment Mechanism (CBAM) officially came into force. The transitional phase started on 1 October 2023 and ends on 1 January 2026.
- In its transitional phase, CBAM will apply to imports of cement, iron and steel, aluminium, fertilisers, electricity and hydrogen.
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But we still have concerns if those cross-border taxes are poorly designed.

- Hard to stop carbon leakage unless we can rationalize carbon leakage via global supply chain.
- Increased price or even inflation brought by cross-border carbon taxes.

Main findings

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  - Import 14.2% additional carbon goods after the implementation of domestic carbon tax. Robust results using Emission Trading Scheme (ETS) or carbon tax price measures.

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- Evidence of Pollution Haven
  - Carbon imports from high-emission (emerging markets with less stringent environmental regulations) increase by 30.3% (39.4%).
- Real Effect of Global Supplier Chain
  - Domestic firms increase their global suppliers after the introduction of carbon tax shock.
  - This effect is concentrated on fossil firms and fossil suppliers.
  - Foreign suppliers expand their investment by 1%, sales growth by 0.9%, labor growth by 1.2% and leverage by 0.8%.

Contribution to the literature

- Literature on carbon leakage
  - e.g. Schroeder and Stracca (2023), Laeven and Popov (2023), Copeland et al., (2022), Ivanov et al., (2023)
  - We provide how international trade can cause carbon production leakage.

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  - We provide micro evidence as well as potential mechanisms underlying the pollution haven effect.

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- Effects of climate risk on global supply chain
  - e.g. Berry et al. (2021), Dai et al. (2021), Darendeli et al. (2022), Choi et al. (2024).
  - We document the impact of carbon leakage on global supply chain.

Hypothesis

Hypothesis 1 Carbon Leakage Hypothesis A simple model

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Hypothesis 3 Real Effect of Fossil Suppliers

- The introduction of carbon taxes in one country creates demands for foreign fossil suppliers. The affected suppliers will invest more and have larger scales in business.

Data sources

We use datasets of different sources.

- Bilateral trade data
  - Source: World Integrated Trade Solution (WITS)
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- Carbon tax data
  - Source: World Bank's Carbon Pricing Dashboard
- Country-level data
  - Source: World Development Indicators (WDI).
  - 195 economies over 1960 to 2021.

Carbon Policy Shock

- Carbon tax dummy: one after the implementation of carbon tax, and zero otherwise.
- ETS dummy: one after the implementation of carbon tax or ETS, whenever comes earlier, and zero otherwise.
- Carbon price: implied nominal price (in US dollars) per ton carbon.

Country	Carbon tax	Average carbon tax price per ton	ETS	Country	Carbon tax	Average carbon tax price per ton	ETS
Argentina	2018	5.2		Latvia	2004	4.7	2005
Austria			2005	Liechtenstein	2008	65.3	
Belgium			2005	Lithuania			2005
Bulgaria			2007	Luxembourg			2005
Canada	2019	31.2		Malta			2005
Chile	2017	5.0		Mexico	2014	3.2	2020
Colombia	2017	5.0		Netherlands			2005
Croatia			2013	New Zealand			2008
Cyprus			2005	Norway	1991	57.7	
Czech Republic			2005	Poland	1990	0.1	2005
Denmark	1992	21.4	2005	Portugal	2015	16.7	2005
Estonia	2000	1.9	2005	Romania			2007
Finland	1990	37.4	2005	Singapore	2019	3.7	
France	2014	39.0	2005	Slovakia			2005
Germany			2005	Slovenia	1996	16.1	2005
Greece			2005	South Africa	2019	8.7	
Hungary			2005	South Korea			2015
Iceland	2010	24.2		Spain	2014	20.1	2005
Ireland	2010	28.2	2005	Sweden	1991	104.1	2005
Italy			2005	Switzerland	2008	71.6	
Japan	2012	2.2		Ukraine	2011	0.2	
Kazakhstan			2013	United Kingdom	2013	21.8	2005

Summary Statistics

	(1)	(2)	(3)	(4)	(5)	(6)
Variable	Obs	Mean	Std. Dev.	p25	p50	p75
Panel A: Bilateral trade level data						
Ln(Carbon imports)	333,919	13.202	3.936	10.567	13.385	16.062
Carbon tax	333,919	0.083	0.277	0.000	0.000	0.000
ETS	333,919	0.137	0.344	0.000	0.000	0.000
Ln(Carbon price)	333,919	0.222	0.845	0.000	0.000	0.000
Ln(GDP)	309,643	24.745	2.355	23.091	24.727	26.479
Ln(GDP per capita)	305,843	8.830	1.465	7.683	8.810	10.199
Carbon tax exporter	333,919	0.141	0.348	0.000	0.000	0.000
Ln(GDP exporter)	321,095	25.785	1.999	24.411	25.989	27.048
Ln(GDP per capita exporter)	319,336	9.302	1.309	8.336	9.426	10.482
High emission countries	319,254	0.477	0.499	0.000	0.000	1.000
Main emerging economies	327,485	0.070	0.255	0.000	0.000	0.000
Panel B: Firm level data						
#Supplier	685,879	0.643	3.699	0.000	0.000	0.000
#Fossil Supplier	685,879	0.026	0.325	0.000	0.000	0.000
#Fossil Fsupplier	685,879	0.014	0.219	0.000	0.000	0.000
Carbon tax	685,879	0.138	0.345	0.000	0.000	0.000
Home carbon tax	675376	0.033	0.178	0.000	0.000	0.000
Home ETS	682975	0.044	0.204	0.000	0.000	0.000
Ln(Assets)	685,879	20.849	3.268	18.506	20.841	22.998
Leverage	638,918	0.249	0.266	0.030	0.190	0.376
Cash	638,518	0.234	0.326	0.048	0.130	0.289
CAPEX	624,752	0.059	0.089	0.010	0.029	0.069
ROA	636,773	-0.032	0.282	-0.033	0.027	0.076
Tobin's Q	583,564	1.808	1.610	0.935	1.261	2.000
Cash flow	495,695	0.069	0.126	0.027	0.072	0.127
Labor growth	407,310	0.086	0.374	-0.040	0.018	0.116
Sales growth	628,110	0.246	1.074	-0.060	0.065	0.232
Fossil dummy	685,879	0.140	0.347	0.000	0.000	0.000

Empirical Specification to Test *Carbon Leakage* Hypothesis

$$\begin{aligned} ln(CarbonImports_{i,j,t}) = \alpha + \beta_1 Carbon_{i,t} + \Gamma_1 Z_{i,t} \\ + \beta_2 Carbon_{j,t} + \Gamma_2 Z_{j,t} + \mu_{i,j} + \delta_t + \epsilon_{i,j,t} \end{aligned} \tag{1}$$

- Carbon Imports is aggregated based on six categories: (1) Aluminium (34); (2) Cement (75); (3) Electricity (4);(4) Fertilisers (26); (5) Hydrogen (4); and (6)Iron and steel (312).
- i, j, t are importer (home country), exporter (foreign country) and year, respectively.
- $CarbonImports_{i,j,t}$ refers to the carbon imports of i from j.
- $Carbon_{i,t}$ and $Carbon_{j,t}$ are carbon emission regulatory policies for country i and j, including the carbon tax dummy, ETS dummy and carbon price.
- $Z_{i,t}$ and $Z_{j,t}$ are importer and exporter level controls, such as GDP and GDP per capita.
- δ_t: Year dummies.
- $\mu_{i,j}$: Country-pair fixed effects.

Results of *Carbon Leakage* Hypothesis

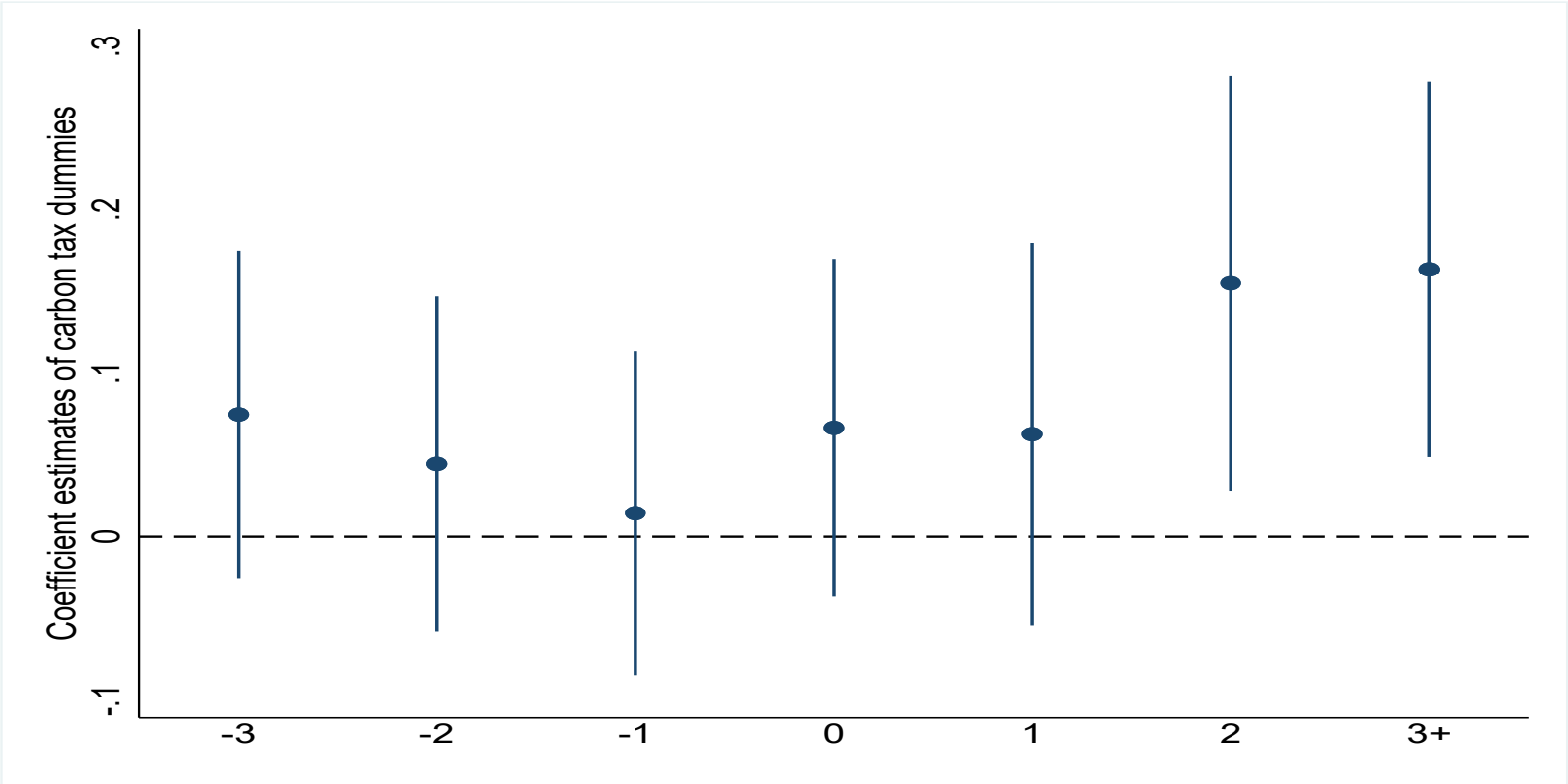
- After the introduction of carbon tax (ETS), the importer country will averagely increase carbon imports by 14.2%(21.2%). robustness results reversed causality

	Ln(Carbon imports)					
	(1)	(2)	(3)	(4)	(5)	(6)
Carbon tax	0.142***	0.141***				
	(0.040)	(0.040)				
ETS			0.212***	0.212***		
			(0.029)	(0.029)		
Ln(Carbon tax price)					0.032**	0.031**
					(0.015)	(0.015)
Carbon tax exporter		-0.058*		-0.060*		-0.059*
		(0.035)		(0.034)		(0.035)
Ln(GDP)	0.444***	0.444***	0.474***	0.474***	0.437***	0.437***
	(0.033)	(0.033)	(0.033)	(0.033)	(0.033)	(0.033)
Ln(GDP per capita)	0.643***	0.644***	0.622***	0.622***	0.648***	0.649***
	(0.059)	(0.059)	(0.059)	(0.059)	(0.059)	(0.059)
Ln(GDP exporter)	-0.189***	-0.199***	-0.193***	-0.203***	-0.188***	-0.198***
	(0.046)	(0.047)	(0.046)	(0.047)	(0.046)	(0.047)
Ln(GDP per capita exporter)	1.397***	1.397***	1.394***	1.394***	1.396***	1.396***
	(0.083)	(0.083)	(0.083)	(0.083)	(0.083)	(0.083)
Constant	-11.514***	-11.247***	-11.961***	-11.688***	-11.399***	-11.129***
	(1.043)	(1.049)	(1.041)	(1.047)	(1.046)	(1.052)
Country-Pair Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Observations	289426	289426	289426	289426	289426	289426
Adjusted R^2	0.785	0.785	0.785	0.785	0.785	0.785

Parallel Trends

The figure presents regression coefficients and 95% confidence bands for carbon imports after the introduction of national carbon tax.

$$ln(CarbonImports_{i,j,t}) = \alpha + \sum_{s=-3}^{3+} \beta_s \times CarbonTax_{i,t}^{s} + \Gamma_1 Z_{i,t} + \Gamma_2 Z_{j,t} + \mu_{i,j} + \delta_t + \epsilon_{i,j,t} \quad (2)$$



Non-carbon imports and green imports under carbon taxes

	Ln(Non-Carbon imports)			Ln(Green imports)		
	(1)	(2)	(3)	(4)	(5)	(6)
Carbon tax	-0.025			0.082		
	(0.031)			(0.053)		
ETS		0.002			0.025	
		(0.022)			(0.038)	
Ln(Carbon tax price)			-0.039***			0.0004
			(0.012)			(0.019)
Ln(GDP)	0.592***	0.595***	0.583***	0.716***	0.712***	0.707***
	(0.022)	(0.023)	(0.022)	(0.040)	(0.040)	(0.040)
Ln(GDP per capita)	0.315***	0.313***	0.318***	0.438***	0.439***	0.443***
	(0.042)	(0.042)	(0.042)	(0.073)	(0.073)	(0.073)
Ln(GDP exporter)	0.054*	0.054*	0.056*	0.222***	0.223***	0.223***
	(0.029)	(0.029)	(0.029)	(0.053)	(0.053)	(0.053)
Ln(GDP per capita exporter)	1.227***	1.227***	1.225***	1.791***	1.790***	1.790***
	(0.054)	(0.054)	(0.054)	(0.099)	(0.099)	(0.099)
Constant	-14.518***	-14.576***	-14.338***	-31.746***	-31.658***	-31.581***
	(0.678)	(0.679)	(0.679)	(1.188)	(1.190)	(1.189)
Country-Pair Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Observations	486971	486971	486971	486975	486975	486975
Adjusted R^2	0.837	0.837	0.837	0.787	0.787	0.787

Empirical Specification to Test *Pollution Haven* Mechanism

$$ln(CarbonImports_{i,j,t}) = \alpha + \beta_1 Carbon_{i,t} + \beta_2 Carbon_{i,t} \times 1(Exporter_{HE(/EM)})_j + \Gamma_1 Z_{i,t} + \Gamma_2 Z_{j,t} + \mu_{i,j} + \delta_t + \epsilon_{i,j,t} \quad (3)$$

- $1(Exporter_{HE})_j$: indicator whether an exporter's average greenhouse gas emission over the sample period is above the global median.
- $1(Exporter_{EM})_j$: indicator whether an exporter is from the main emerging countries.

Results of *Pollution Haven* Mechanism

- After the introduction of carbon tax, the importer country will averagely increase carbon imports from high-emission (emerging countries) by 30.3%(39.4%). robustness results

	Ln(Carbon imports)					
	(1)	(2)	(3)	(4)	(5)	(6)
Carbon tax	-0.014	0.118***				
	(0.051)	(0.042)				
ETS			0.094**	0.187***		
			(0.036)	(0.030)		
Ln(Carbon tax price)					-0.022	0.023
					(0.020)	(0.015)
Carbon tax$\times 1(Exporter_{HE})$	0.303***					
	(0.078)					
Carbon tax$\times 1(Exporter_{EM})$		0.394***				
		(0.130)				
ETS$\times 1(Exporter_{HE})$			0.226***			
			(0.053)			
ETS$\times 1(Exporter_{EM})$				0.422***		
				(0.096)		
Ln(Carbon tax price)$\times 1(Exporter_{HE})$					0.102***	
					(0.028)	
Ln(Carbon tax price)$\times 1(Exporter_{EM})$						0.144***
						(0.046)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Country-Pair Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Observations	284090	289202	284090	289202	284090	289202
Adjusted R^2	0.785	0.785	0.785	0.785	0.785	0.785

Empirical Specification of *Supply Chain-level Effect*

$$\begin{aligned} 1(FossilConnection)_{i,j,t} = \alpha + \beta_1 Carbon_{i,t} + \beta_2 Carbon_{i,t} \times 1(Foreign)_{i,j} + \Gamma_1 Z_{i,t} \\ + \beta_3 Carbon_{j,t} + \Gamma_2 Z_{j,t} + \mu_{i,j} + \delta_t + \epsilon_{i,j,t} \end{aligned} \tag{4}$$

- i, j, t are customer, supplier and year, respectively.
- $1(FossilConnection)_{i,j,t}$ is a dummy variable, indicating a domestic customer connect to a fossil supplier. If the customer establishes a relationship with the fossil supplier, this dummy is set to be one, otherwise zero.
- $Carbon_{i,t}$ and $Carbon_{j,t}$ indicate whether the country of customer i or supplier j has adopted the carbon related policy respectively.

Result of Supply-Chain Level Result

- After the introduction of carbon tax (ETS), customers increase 3.77%(5.78%) fossil suppliers abroad.

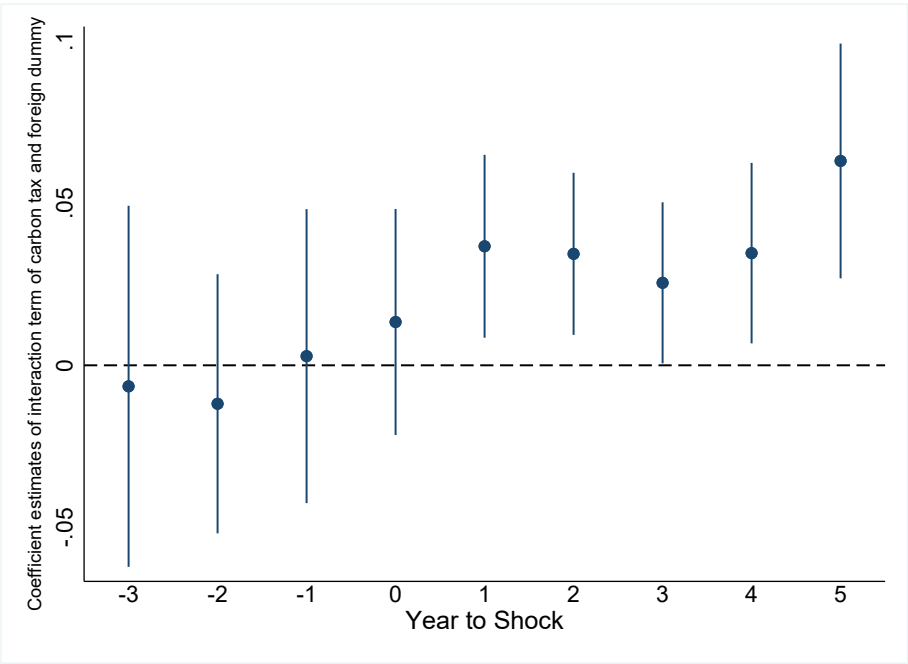
	$1(FossilConnection)$			
	(1)	(2)	(3)	(4)
Customer Carbon Tax*$1(Foreign)$	0.073***		0.066***	
	(0.025)		(0.023)	
Customer Carbon Tax	-0.066***			
	(0.022)			
Supplier Carbon Tax	0.004			
	(0.021)			
Customer ETS*$1(Foreign)$		0.109***		0.073***
		(0.019)		(0.015)
Customer ETS		-0.117***		
		(0.016)		
Supplier ETS		0.015		
		(0.013)		
Customer Ln(Assets)	0.013**	0.012***	0.007**	0.007**
	(0.005)	(0.004)	(0.003)	(0.003)
Customer Tobin's Q	0.004**	0.004**	0.002**	0.002**
	(0.002)	(0.001)	(0.001)	(0.001)
Customer Cashflow	-0.012	-0.011	-0.000	0.000
	(0.008)	(0.008)	(0.007)	(0.007)
Supplier Ln(Assets)	0.021***	0.021**	0.023**	0.023**
	(0.008)	(0.008)	(0.011)	(0.011)
Supplier Tobin's Q	0.009***	0.009***	0.005***	0.005***
	(0.002)	(0.002)	(0.001)	(0.001)
Supplier Cashflow	-0.040*	-0.039*	-0.038*	-0.038
	(0.023)	(0.022)	(0.023)	(0.023)
Constant	-0.822***	-0.787***	-0.739**	-0.746**
	(0.300)	(0.287)	(0.327)	(0.326)
Sup.-Cus. FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	No	No
Sup.-Ctry-Year FE	No	No	Yes	Yes
Cus.-Ctry-Year FE	No	No	Yes	Yes
Observations	165756	165756	165650	165650
Adjusted R^2	0.091	0.094	0.157	0.158

Parallel Trends

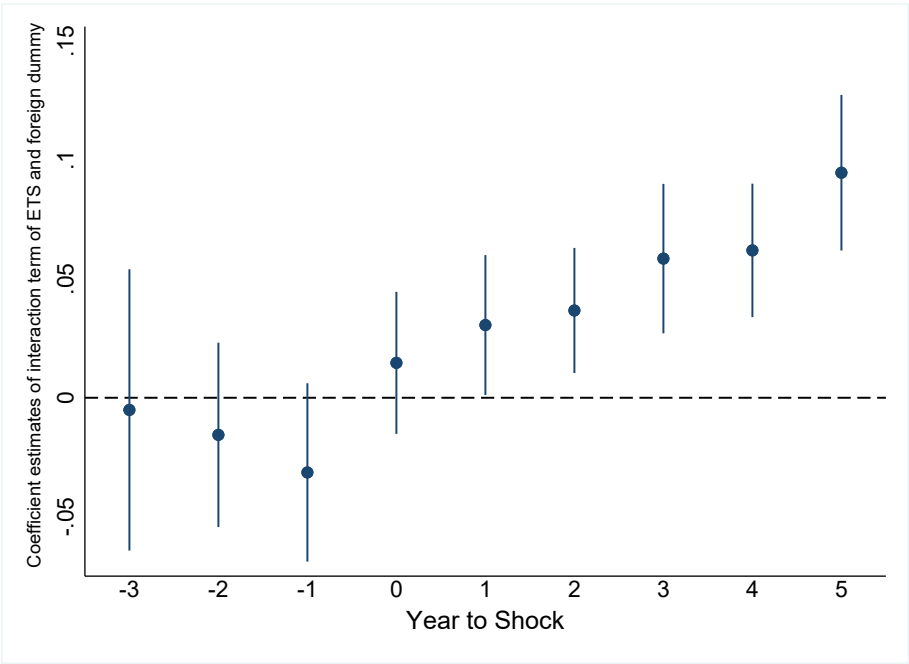
The figure presents regression coefficients and 95% confidence bands for carbon imports after the introduction of national carbon tax /ETS.

$$1(FossilConnection)_{i,j,t} = \alpha + \sum_{s=-3}^{5} \beta_s \times CarbonTax^{s}_{i,t} \times 1(Foreign)_{i,j} + \Gamma_1 Z_{i,t} + \Gamma_2 Z_{j,t} + \mu_{i,j} + \delta_t + \epsilon_{i,j,t} \quad (5)$$

Panel A: Carbon Tax



Panel B: ETS



Financial Constraint Channel of Supply Chain Effect

	1(*FossilConnection*)			
	Low KZ (1)	High KZ (2)	Low KZ (3)	High KZ (4)
Customer Carbon Tax*1(*Foreign*)	0.006	0.121***		
	(0.030)	(0.021)		
Customer ETS*1(*Foreign*)			0.013	0.087***
			(0.023)	(0.024)
Customer Ln(Assets)	0.006***	0.008	0.006***	0.008
	(0.002)	(0.006)	(0.002)	(0.006)
Customer Tobin's Q	0.001	0.002**	0.001	0.002**
	(0.001)	(0.001)	(0.001)	(0.001)
Customer Cashflow	-0.003	-0.002	-0.003	-0.002
	(0.009)	(0.010)	(0.009)	(0.010)
Supplier Ln(Assets)	0.008	0.031**	0.008	0.031**
	(0.006)	(0.013)	(0.006)	(0.013)
Supplier Tobin's Q	0.004**	0.006***	0.004**	0.006***
	(0.002)	(0.002)	(0.002)	(0.002)
Supplier Cashflow	-0.003	-0.044	-0.003	-0.044
	(0.022)	(0.028)	(0.022)	(0.028)
Constant	-0.333**	-0.976**	-0.337**	-0.978**
	(0.151)	(0.439)	(0.147)	(0.437)
Sup.-Cus. FE	Yes	Yes	Yes	Yes
Sup.-Ctry-Year FE	Yes	Yes	Yes	Yes
Cus.-Ctry-Year FE	Yes	Yes	Yes	Yes
Observations	78454	77748	78454	77748

Empirical Specification to Test *Customer's Real Effect*

$$\begin{aligned} SupplierNumber_{f,c,t} = \alpha + \beta_1 Carbon_{c,t} + \beta_2 Carbon_{c,t} \times 1(Fossil_f) \\ + \Gamma_1 Z_{f,t} + \mu_f + \delta_t + \epsilon_{f,c,t} \end{aligned} \tag{6}$$

- f, c and t represent firm, country and year, respectively.
- $SupplierNumber_{f,c,t}$ is the annual aggregated amount of suppliers that can be traced to firm f at year t.
- $Carbon_{c,t}$ refers to whether a country c implements national carbon tax or ETS in year t.
- $1(Fossil_f)$ is a dummy variable indicating whether firm f belongs to the fossil sector.
- Firm-level controls: firm size (assets), leverage, cash holding, capital expenditure, ROA, Tobin's Q and cash flow.
- μ_f is firm fixed effect and δ_t is year fixed effect.

Results of *Customer's Real Effect*

	#Supplier			#Fossil Supplier			#Fossil FSupplier		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Carbon tax	0.123*			-0.029***			-0.022***		
	(0.069)			(0.005)			(0.003)		
ETS		0.212***			0.011**			-0.013***	
		(0.056)			(0.005)			(0.003)	
Ln(Carbon tax price)			0.096***			-0.015***			-0.008***
			(0.034)			(0.002)			(0.002)
Carbon tax				0.115***			0.077***		
$\times$*Fossil*				(0.028)			(0.020)		
ETS					0.263***			0.145***	
$\times$*Fossil*					(0.052)			(0.038)	
Ln(Carbon tax price)						0.051***			0.034***
$\times$*Fossil*						(0.013)			(0.008)
Ln(Assets)	0.196***	0.201***	0.197***	0.000	0.003	0.001	0.002	0.003*	0.002
	(0.031)	(0.031)	(0.031)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Leverage	0.121**	0.120**	0.119**	-0.008*	-0.008*	-0.008	-0.005	-0.005	-0.005
	(0.056)	(0.056)	(0.056)	(0.005)	(0.005)	(0.005)	(0.003)	(0.003)	(0.003)
Cash	-0.190***	-0.197***	-0.189***	0.007**	0.004	0.006*	-0.000	-0.001	-0.001
	(0.048)	(0.048)	(0.048)	(0.003)	(0.003)	(0.003)	(0.002)	(0.002)	(0.002)
CAPEX	0.437***	0.431***	0.432***	0.004	-0.001	0.005	0.005	0.003	0.004
	(0.087)	(0.087)	(0.087)	(0.009)	(0.009)	(0.009)	(0.007)	(0.007)	(0.007)
ROA	-0.683***	-0.709***	-0.671***	-0.027	-0.025	-0.027*	-0.031***	-0.028**	-0.031***
	(0.201)	(0.201)	(0.201)	(0.017)	(0.017)	(0.017)	(0.012)	(0.012)	(0.012)
Tobin's Q	0.018*	0.019**	0.018*	-0.002***	-0.002**	-0.002***	-0.001**	-0.001**	-0.001**
	(0.009)	(0.009)	(0.009)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Cash flow	0.726***	0.743***	0.712***	0.028*	0.019	0.027	0.028**	0.023**	0.026**
	(0.204)	(0.204)	(0.203)	(0.017)	(0.017)	(0.017)	(0.012)	(0.012)	(0.012)
Constant	-3.499***	-3.649***	-3.536***	0.038	-0.041	0.030	-0.017	-0.038	-0.030
	(0.672)	(0.668)	(0.671)	(0.051)	(0.048)	(0.050)	(0.037)	(0.036)	(0.036)
Firm Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	430428	430428	430428	430428	430428	430428	430428	430428	430428
Adjusted R^2	0.413	0.413	0.413	0.436	0.438	0.436	0.424	0.425	0.424

Empirical Specification to Test *Supplier-level Real Effect*

$$SupplierPerf_{s,t} = \alpha + \beta_1 Carbon_{k,t} + \Gamma_1 Z_{s,t} + \mu_s + \delta_t + \epsilon_{s,t} \quad (7)$$

- s, k and t represent supplier, customer's country and year, respectively.
- $SupplierPerf_{s,t}$ is the supplier's operating performance at year t, including the capital expenditure (CAPEX), R&D, sales growth, employment growth, and leverage.
- $Carbon_{k,t}$ is a dummy variable capturing whether the customer's country k has implemented national carbon tax or ETS.
- $Z_{s,t}$ are supplier's firm level controls, including firm size, Tobin's Q and cash flow.
- Supplier fixed effect μ_f and year fixed effect δ_t.

Results of *Supplier's Real Effect*

- After the introduction of carbon tax, foreign supplier increase investment by 1%, sales growth by 0.9%, labor growth by 1.2% and leverage by 0.8%.

Panel A: Real Effect under Carbon Tax	CAPEX (1)	CAPEX_R&D (2)	Sales growth (3)	Employment growth (4)	Leverage (5)
Home carbon tax	0.010***	0.008***	0.009*	0.012***	0.008***
	(0.001)	(0.001)	(0.005)	(0.003)	(0.003)
Ln(Assets)	0.003***	0.002***	0.069***	0.061***	0.071***
	(0.000)	(0.000)	(0.004)	(0.002)	(0.002)
Tobin's Q	0.002***	0.003***	0.020***	0.010***	0.005***
	(0.000)	(0.000)	(0.002)	(0.001)	(0.001)
Cash flow	0.108***	0.105***	1.140***	0.465***	-0.089***
	(0.002)	(0.002)	(0.025)	(0.013)	(0.008)
Constant	-0.017**	0.007	-1.450***	-1.303***	-1.267***
	(0.008)	(0.009)	(0.090)	(0.047)	(0.039)
Firm Fixed Effect	Yes	Yes	Yes	Yes	Yes
Year Fixed Effect	Yes	Yes	Yes	Yes	Yes
Observations	398333	398089	400942	274925	404114
Adjusted R^2	0.401	0.461	0.146	0.108	0.513

Panel B: Real Effect under ETS	CAPEX (1)	CAPEX_R&D (2)	Sales Growth (3)	Labor Growth (4)	Leverage (5)
Home ETS	0.007***	0.007***	0.002	0.007**	0.002
	(0.001)	(0.001)	(0.005)	(0.003)	(0.002)
Ln(Assets)	0.003***	0.002***	0.068***	0.060***	0.071***
	(0.000)	(0.000)	(0.004)	(0.002)	(0.002)
Tobin's Q	0.002***	0.003***	0.020***	0.010***	0.005***
	(0.000)	(0.000)	(0.002)	(0.001)	(0.001)
Cash flow	0.109***	0.105***	1.141***	0.466***	-0.088***
	(0.002)	(0.002)	(0.024)	(0.013)	(0.008)
Constant	-0.018**	0.006	-1.437***	-1.294***	-1.267***
	(0.008)	(0.009)	(0.089)	(0.047)	(0.039)
Firm Fixed Effect	Yes	Yes	Yes	Yes	Yes
Year Fixed Effect	Yes	Yes	Yes	Yes	Yes
Observations	405245	404996	407860	279158	411034
Adjusted R^2	0.401	0.462	0.146	0.108	0.512

Financial Constraint of Supplier's Real Effect

Panel A: Real Effect under Carbon Tax	CAPEX (1)	CAPEX_RD (2)	Sales Growth (3)	Labor Growth (4)	Leverage (5)
Home carbon tax*KZ	0.009***	0.010**	0.183***	0.064***	0.071***
	(0.003)	(0.004)	(0.028)	(0.020)	(0.018)
Home carbon tax	1.056***	0.901***	2.614***	1.544***	1.070***
	(0.077)	(0.093)	(0.452)	(0.346)	(0.283)
Firm Controls	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Observations	407372	407372	411480	279153	413469
Adjusted R^2	0.384	0.447	0.227	0.115	0.510
Panel B: Real Effect under ETS	CAPEX (1)	CAPEX_RD (2)	Sales Growth (3)	Labor Growth (4)	Leverage (5)
Home ETS*KZ	0.006***	0.011***	0.163***	0.071***	0.055***
	(0.002)	(0.004)	(0.026)	(0.017)	(0.017)
Home ETS	0.792***	0.737***	1.388***	1.004***	0.371
	(0.070)	(0.082)	(0.390)	(0.318)	(0.245)
Firm Controls	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Observations	414314	414314	418431	283403	420423
Adjusted R^2	0.384	0.448	0.227	0.115	0.510

Conclusion

- This paper provides evidence for production leakage via international trade.
- Local firms make sourcing decisions (i.e. carbon imports) in response to exogenous shocks of national carbon taxes, ETS or carbon tax price.
- Carbon production opportunities are shifted to countries with more lenient environmental regulations. (Evidence of Pollution Haven).
- Further firm-level and supplier-level information reveal the real impact of firm decision on foreign suppliers.
- Domestic regulatory carbon taxes inadvertently benefit foreign carbon suppliers.
- Our findings underscore the unintended consequences of the unilateral carbon policies on foreign countries

Global CO_2 Emission

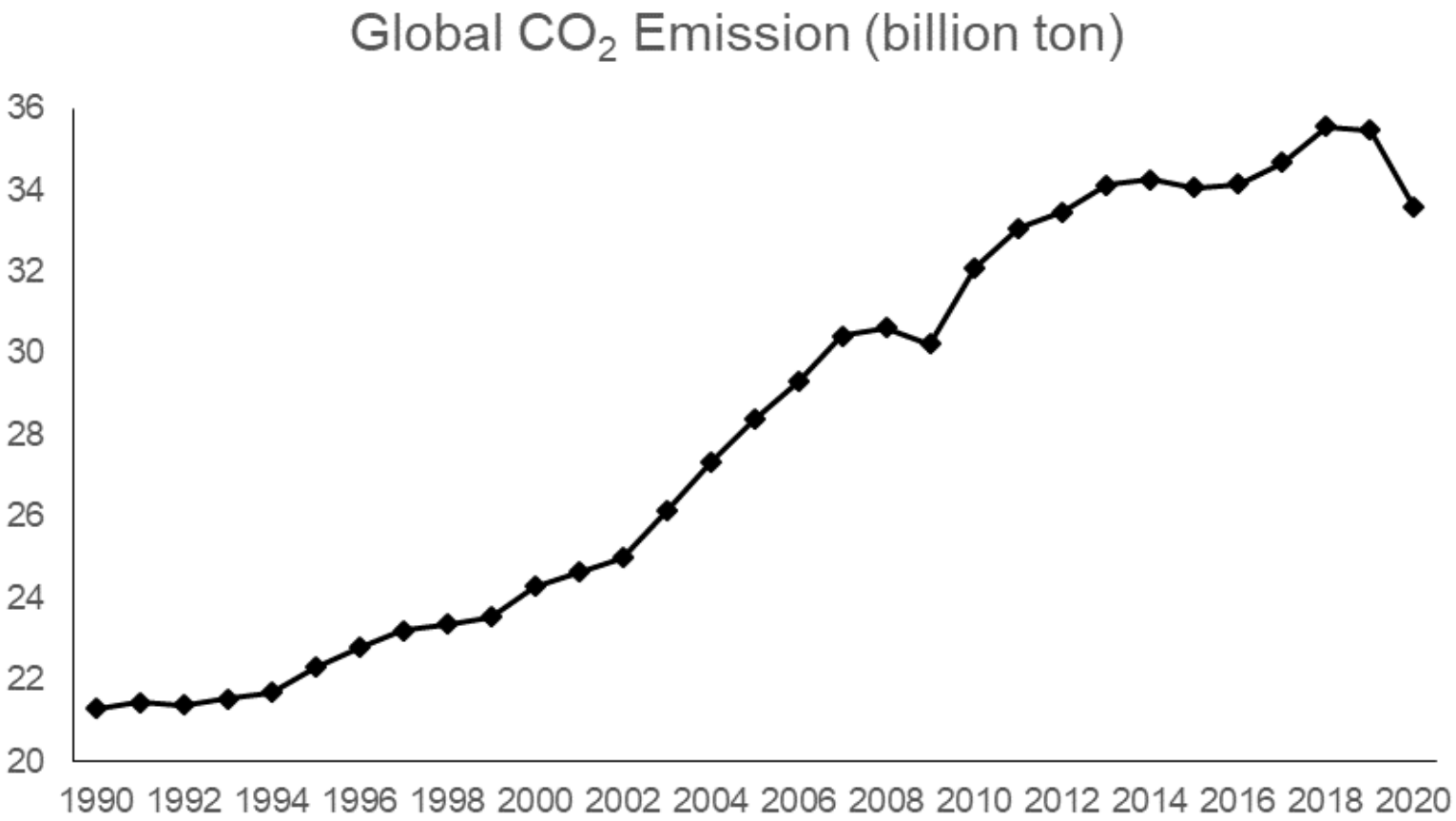


Figure: Global CO_2 Emission Revolution

Data source: World Bank WDI Database.

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A simple model

- Consider a representative consumer in this economy with a CES utility function

$$U = \left(\int_0^1 \left(q(\omega) \right)^{\frac{\sigma-1}{\sigma}} d\omega \right)^{\frac{\sigma}{\sigma-1}}$$

  - $q(\omega)$is the quantity of consumption of good ω
  - $\omega \in [0,1]$ is a continuum of goods
  - $\sigma > 1$ is the elasticity of substitution between goods.
- Each country draws a productivity for each good $\varphi_n(\omega)$ from a country-specific Frechet distribution, $F(\varphi) = e^{-T_n \varphi^{-\theta}}$ with L_n units of labor.
- Pollution is costly. With pollution tax t_n, countries would choose a optimal fraction $a_n(\omega)$ of its labor to abate pollution, and then use the remaining fraction $(1 - a_n(\omega))$ of labor to produce goods. The net output of a country for good ω is thus:

$$q_n(\omega) = (1 - a_n(\omega)) \left[\varphi_n(\omega) L_n(\omega) \right] \tag{8}$$

  - $\varphi_n(\omega)$ is the drawn production efficiency
  - $L_n(\omega)$ is the labor input of good ω in country n.

A simple model cont'd

- The level of emissions associated with the good production is:

$$z_n(\omega) = [1 - a_n(\omega)]^{\frac{1}{\gamma}} L_n(\omega) \tag{9}$$

  - $0 < \gamma < 1$ is the pollution elasticity
- Expressing $(1 - a_n(\omega))$ as a function of pollution from Equation (9) and substituting it into Equation (8), the net output can be expressed as:

$$q_n(\omega) = \varphi_n(\omega) \left[z_n(\omega)\right]^{\gamma} \left[L_n(\omega)\right]^{1-\gamma} \tag{10}$$

- The optimal choice of pollution abatement is equivalent to the choice of emission level. The cost of an input bundle in country n is:

$$c_n = t_n^{\gamma} w_n^{1-\gamma} \tag{11}$$

  - t_n is the pollution tax
  - w_n is the wage in country n.
- The production cost of good ω in country n is then

$$p_n(\omega) = c_n / \varphi_n(\omega) \tag{12}$$

Model Equilibrium under international trade

- Under perfect competition, The price of a good ω produced in country i and sold in country n is

$$P_{ni}(\omega) = c_i d_{ni} / \varphi_i(\omega)$$

  - d_{ni} is iceberg trade costs from country i to country n
  - $d_{ni} = d_{in}$.
- Consumers choose the lowest priced goods sold in in their market so

$$P_n(\omega) = \min\{P_{n1}(\omega), \ldots, P_{ni}(\omega), \ldots, P_{nN}(\omega)\}$$

  - The demand of each good, $q_n(\omega)$, is then given by

$$q_n(\omega) = \frac{I_n}{P_n}\left(\frac{P_n(\omega)}{P_n}\right)^{-\sigma}$$

  - P_n is the aggregate price of country n. Specifically, P_n is given by,

$$P_n \equiv \left(\int_0^1 (P_n(\omega))^{1-\sigma} d\omega\right)^{\frac{1}{1-\sigma}}$$

Model Equilibrium under international trade Cont'd

- Based on Eaton and Kortum (2002), the share of expenditures by country n on goods produced in country i is

$$\pi_{ni} = \frac{X_{ni}}{X_n} = \frac{T_i \left(c_i d_{ni}\right)^{-\theta}}{\Phi_n} \tag{13}$$

  - X_{ni} is the expenditure of country n spent on goods from country i
  - X_n is the total expenditure of country n,
  - $\Phi_n = \sum_{i=1}^{N} T_i \left(c_i d_{ni}\right)^{-\theta}$.
- Equilibrium condition with pollution tax t_i

$$\frac{w_n L_n}{1-\gamma} = \sum_{j=1}^{N} X_{jn} \tag{14}$$

- Substituting Equation (13) in Equation (14), we have

$$\frac{L_n w_n}{1-\gamma} = \sum_{j=1}^{N} \frac{T_n \left(c_n d_{jn}\right)^{-\theta}}{\Phi_j} \frac{L_j w_j}{1-\gamma} \tag{15}$$

Model Implication

- A tighten carbon regulation is equivalent to higher production costs.
  - Such higher carbon costs lead a country to reduce its fossil consumption and cut investment plans, which in turn lower the total production of goods.
  - At the same time, the country is expected to import more goods from its trading partners.
- Based on Equation (13), The increase in country i's pollution tax t_i increases the input bundle cost, c_i, and it leads to increases in costs and prices of all goods produced by the country. Increases in costs and prices of all goods by the country consequently reduces the attractiveness of its products and decrease its share in other countries' expenditure baskets,

$$\frac{\partial \pi_{ni}}{\partial t_i} = -\theta\gamma \frac{1}{t_i} \left[T_i \left(c_i d_{ni} \right)^{-\theta} \right] \frac{1 - \pi_{ni}}{\Phi_n} < 0 \tag{16}$$

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Carbon Leakage at country level

Panel A: Country-level	CO_2 kg per GDP				ln(Carbon imports)			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Carbon tax	-0.104***	-0.081***			0.307***	0.142***		
	(0.028)	(0.026)			(0.038)	(0.043)		
ETS			-0.066***	-0.039***			0.580***	0.432***
			(0.014)	(0.013)			(0.030)	(0.035)
Ln(GDP per capita)	-0.658***	-0.865***	-0.640***	-0.862***	0.554***	1.096***	0.289***	0.805***
	(0.042)	(0.070)	(0.044)	(0.074)	(0.075)	(0.113)	(0.070)	(0.110)
Ln(GDP)	0.458***	0.720***	0.440***	0.713***	-0.273***	-0.890***	0.010	-0.504***
	(0.038)	(0.065)	(0.040)	(0.070)	(0.073)	(0.103)	(0.067)	(0.106)
Ln(CPI)		-0.071***		-0.071***		-0.042**		-0.045**
		(0.018)		(0.018)		(0.021)		(0.020)
Ln(REER)		-0.004		0.013		0.061		-0.058
		(0.037)		(0.040)		(0.066)		(0.061)
Constant	-4.982***	-9.326***	-4.714***	-9.270***	2.844**	13.547***	-1.747*	7.086***
	(0.633)	(1.014)	(0.673)	(1.109)	(1.146)	(1.684)	(1.061)	(1.720)
Country Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	4803	2427	4803	2427	4451	2178	4451	2178
Adjusted R^2	0.868	0.918	0.868	0.917	0.914	0.932	0.921	0.937

Carbon Leakage at product level

Panel B: Product-level	Ln(Product imports)		Product imports/GDP		Product imports/Total imports	
	(1)	(2)	(3)	(4)	(5)	(6)
Carbon tax × Carbon product	0.187***		0.008***		0.022***	
	(0.019)		(0.002)		(0.005)	
Carbon tax	-0.058**		-0.007***		-0.017***	
	(0.026)		(0.003)		(0.006)	
ETS × Carbon product		0.277***		0.021***		0.053***
		(0.013)		(0.001)		(0.003)
ETS		0.026		0.015***		0.027***
		(0.021)		(0.002)		(0.005)
Ln(GDP)	0.355***	0.398***	-0.077***	-0.063***	-0.159***	-0.125***
	(0.053)	(0.053)	(0.005)	(0.005)	(0.012)	(0.013)
Ln(GDP per capita)	0.427***	0.389***	0.060***	0.049***	0.159***	0.129***
	(0.058)	(0.058)	(0.005)	(0.005)	(0.013)	(0.014)
Constant	0.283	-0.452	1.442***	1.214***	2.818***	2.227***
	(0.842)	(0.862)	(0.079)	(0.076)	(0.202)	(0.213)
Country×Product Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Observations	17123816	17123816	17123832	17123832	15301286	15301286
Adjusted R^2	0.806	0.806	0.690	0.690	0.707	0.707

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Reversed causality of *Carbon Leakage* Hypothesis

	$Carbontax_t$ (1)	Ln(Carbon imports) (2)
$Ln(CarbonImports)_{t-1}$	0.0005	
	(0.0004)	
Randomized carbon tax		-0.005
		(0.013)
Ln(GDP)	-0.1322***	0.426***
	(0.0050)	(0.032)
Ln(GDP per capita)	0.0475***	0.651***
	(0.0052)	(0.059)
Ln(GDP exporter)	0.0240***	-0.186***
	(0.0061)	(0.046)
Ln(GDP per capita exporter)	-0.0150	1.395***
	(0.0121)	(0.083)
Constant	2.4774***	-11.178***
	(0.1596)	(1.042)
Country-Pair Fixed Effect	Yes	Yes
Year Fixed Effect	Yes	Yes
Observations	243703	289426
Adjusted R^2	0.718	0.785

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Subcategories of carbon imports under carbon taxes

Panel A: Subcategories of Carbon Import under Carbon tax	Ln(Carbon imports)			
	Aluminium	Iron and steel	Cement	Other carbon goods
	(1)	(2)	(3)	(4)
Carbon tax	0.160**	0.171***	0.189**	0.068
	(0.081)	(0.058)	(0.078)	(0.080)
Importer Country Controls	Yes	Yes	Yes	Yes
Exporter Country Controls	Yes	Yes	Yes	Yes
Country-Pair Fixed Effect	Yes	Yes	Yes	Yes
Year Fixed Effect	Yes	Yes	Yes	Yes
Observations	289426	289426	289426	289426
Adjusted R^2	0.727	0.712	0.732	0.705

Panel B: Subcategories of Carbon Import under ETS				
	Aluminium	Iron and steel	Cement	Other carbon goods
	(1)	(2)	(3)	(4)
ETS	0.247***	0.166***	0.058	0.098
	(0.059)	(0.043)	(0.059)	(0.061)
Importer Country Controls	Yes	Yes	Yes	Yes
Exporter Country Controls	Yes	Yes	Yes	Yes
Country-Pair Fixed Effect	Yes	Yes	Yes	Yes
Year Fixed Effect	Yes	Yes	Yes	Yes
Observations	289426	289426	289426	289426
Adjusted R^2	0.727	0.712	0.732	0.705

Panel C: Subcategories of Carbon Import under Carbon Price				
	Aluminium	Iron and steel	Cement	Other carbon goods
	(1)	(2)	(3)	(4)
Ln(Carbon tax price)	0.083***	0.034	0.048*	-0.040
	(0.029)	(0.021)	(0.028)	(0.029)
Importer Country Controls	Yes	Yes	Yes	Yes
Exporter Country Controls	Yes	Yes	Yes	Yes
Country-Pair Fixed Effect	Yes	Yes	Yes	Yes
Year Fixed Effect	Yes	Yes	Yes	Yes
Observations	289426	289426	289426	289426
Adjusted R^2	0.727	0.712	0.732	0.705

Pollution Haven Hypothesis robustness

	Ln(Carbon imports)		
	(1)	(2)	(3)
Carbon tax	0.141***		
	(0.041)		
ETS		0.206***	
		(0.029)	
Ln(Carbon tax price)			0.032**
			(0.015)
Carbon tax $\times Exporter_{China}$	0.440*		
	(0.242)		
Carbon tax $\times Exporter_{US}$	-0.347***		
	(0.112)		
ETS $\times Exporter_{China}$		0.617***	
		(0.158)	
ETS $\times Exporter_{US}$		-0.155*	
		(0.082)	
Ln(Carbon tax price) $\times Exporter_{China}$			0.111*
			(0.063)
Ln(Carbon tax price) $\times Exporter_{US}$			-0.170***
			(0.036)
Controls	Yes	Yes	Yes
Country-Pair Fixed Effect	Yes	Yes	Yes
Year Fixed Effect	Yes	Yes	Yes
Observations	289426	289426	289426
Adjusted R^2	0.785	0.785	0.785

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