Climate Trade Costs:

Extreme Weather, Transportation, and Supply Chains

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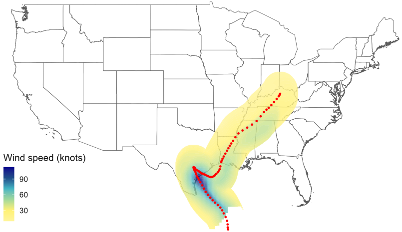

(a) E.g. Hurricane Harvey (Aug. 2017)

(b) E.g. Port of Houston (Aug. 2017)

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Q1: What are the impacts of tropical cyclones on infrastructure? On trade? (positive)

Q2: What are the implications for infrastructure policy? (normative)

This paper

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3. Infrastructure policy
   - Sufficient statistics: Welfare gains of port-level investment
   - Policy myopia w.r.t. CΔ + rerouting → misallocation of future port investment

Contribution

- Natural disasters and production networks
  (Balboni et al. 2024; Barrot et al. 2016; Blaum et al. 2024; Boehm et al. 2019; Carvalho et al. 2021; Castro-Vincenzi et al. 2024; Clark et al. 2024; Martinez 2024; Pankratz et al. 2021; Rabano et al. 2024)
  Contribution: Rerouting as response to climate change + congestion spillovers

- Transportation costs/infrastructure and trade
  (Allen and Arkolakis 2022; Allen, Fuchs, et al. 2025; Brancaccio et al. 2020, 2024; Ducruet et al. 2024; Fajgelbaum et al. 2020; Ganapati et al. 2024; Wong et al. 2022)
  Contribution: Infrastructure policy with weather disruptions

- Economic geography of climate change
  (Balboni 2025; Bilal et al. 2023; Cruz et al. 2024; Desmet, Kopp, et al. 2021; Desmet and Rossi-Hansberg 2015; Rudik et al. 2021)
  Contribution: Transportation = spatial propagation of local weather shocks

Outline

Data

- Brazilian maritime imports, shipment level (2014-2023, S&P Panjiva) $\approx$ 9M shipments data
  Trade relationships + maritime routes

- Daily port activity & volume (2019-2023, PortWatch) $\approx$ 1.6k ports
  Port-level traffic and capacity

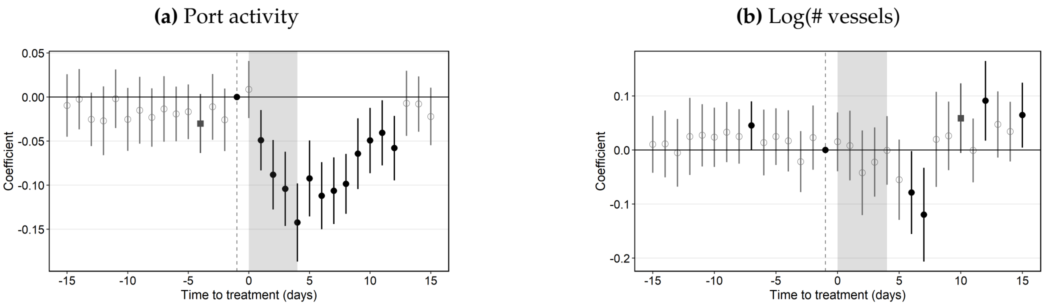
- Historical tropical cyclone tracks (2014-2023, IBTrACS) $\approx$ 600 cyclones at 3h resolution data
  Weather shocks to ports

- Global tropical cyclone hazard (present and RCP8.5, STORM) = 10k synthetic cyclone seasons data
  Tropical cyclone climate

Outline

Fact 1: Port disruptions (details)

- Weather shocks: 18 m/s of maximum sustained wind speed (ZULU) (Sum. cyclones)
- Data: daily port-level vessel count & volume TEU (2019-2023, 621 ports)



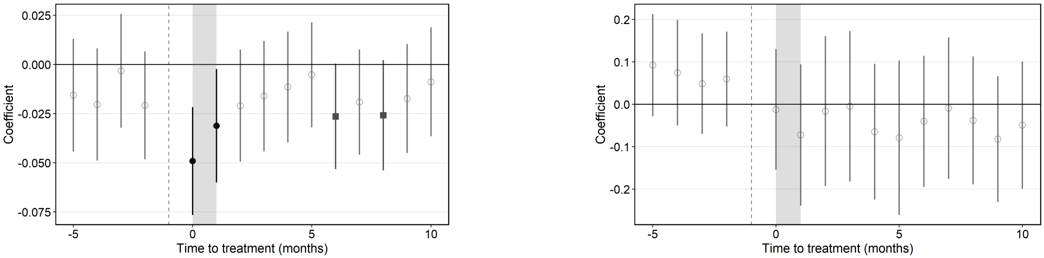
- Port disruptions ≈ 1 week (placebo) (het. exposure) (het. containerized)

Fact 2: Routing disruptions (details)

- Data: Brazilian imports $\xrightarrow{\text{agg.}}$ buyer - supplier - destination port - $\overbrace{\text{origin port}}^{\text{treatment}}$ (monthly)
- Design: stacked DiD, controlling for pre-shock relationship-route characteristics
- Variation: within relationships $\{b, s\}$, across routes $\{p_o, p_d\}$, for routes active before cyclone (6m)

(a) Route activity

(b) Log weight



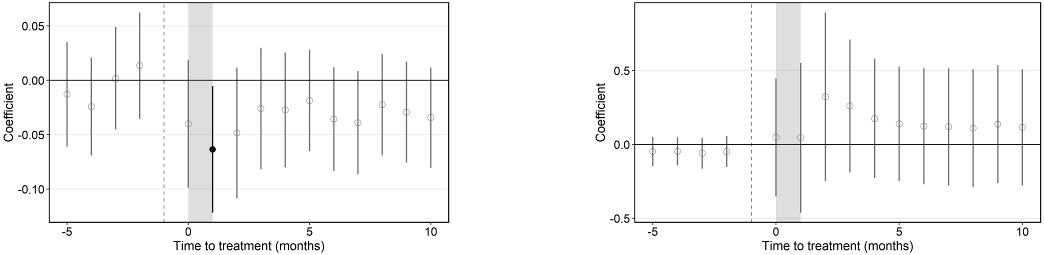
- Temporary decrease in the probability of trading through affected port: ↓ 7% (3-month average)

intensive margins | alt. wind speed | alt. exposure | het. containerized | het. treatment order

Fact 3: Sourcing disruptions (details)

- Data: Brazilian imports $\xrightarrow{\text{agg.}}$ buyer - supplier (monthly)
- Design: stacked DiD, controlling for pre-shock relationship characteristics
- Variation: within buyers, across suppliers, for relationships active before cyclone (6m)

(a) Relationship activity **(b)** Log weight



- Most disruptions absorbed by rerouting + ex-ante adaptation

alt. exposure | het. treatment order | het. containerized

Outline

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Model overview

- Goal = quantify the impacts of (i) CΔ at ports + (ii) firm-level responses (+ spillovers!)

- Model (static) = spatial production network + transportation network
  - Geography = regions linked through land + sea routes
  - Firms use labor + intermediate inputs supplied through the optimal route (facts 2 & 3)
  - Transportation costs = distance + port capacity + $\underbrace{\text{port traffic}}_{\text{spillover}}$ + $\underbrace{\text{weather risk}}_{\text{C}\Delta}$ (fact 1)

Firms (Balboni et al. 2024)

- Firms produce by choosing a cost-minimizing 'technique' = supplier-buyer match ϕ + delivery route r

$$y_i(\phi,r) = a_{n(i)} l_i^{1-\alpha} [z(\phi) x_i(\phi,r)]^\alpha \chi \tag{1}$$

- Marginal cost of using technique (ϕ, r)

$$c_i(\phi,r) = \frac{w_{n(i)}^{1-\alpha}}{a_{n(i)}} \left(\tau_{n(j)n(i)}(r) \frac{c_j(\phi)}{z(\phi)} \right)^\alpha \tag{2}$$

where

- $w_{n(i)}$ = local wage rate
- $a_{n(i)}$ = fundamental region-level productivity
- $z(\phi)$ = match-specific productivity assumptions
- $\tau_{n(j)n(i)}(r)$ = bilateral transportation costs of route r $\Rightarrow$ Key distinction from Balboni et al. (2024)

Shipping (Allen and Arkolakis 2022; Ganapati et al. 2024)

- Transportation costs from n to $n' \to$ routes r composed of set $\mathcal{B}_r$ of legs + set $\mathcal{P}_r$ of ports

$$\tau_{nn'}(r) = \prod_{k=1}^{|\mathcal{B}_r|} d_{r_{k-1},r_k} \prod_{m=1}^{|\mathcal{P}_r|} t_{p(r)_m} \tag{3}$$

- Leg-level costs d_{r_{k-1},r_k}
- Port-level costs $t_{p(r)_m}$

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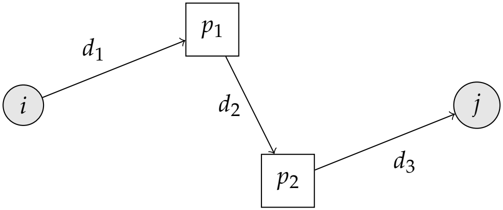

$$\tau_{nn'}(r) = d_1 \cdot d_2 \cdot d_3 \cdot t_{p_1} \cdot t_{p_2}$$

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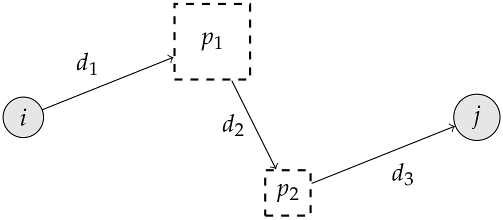

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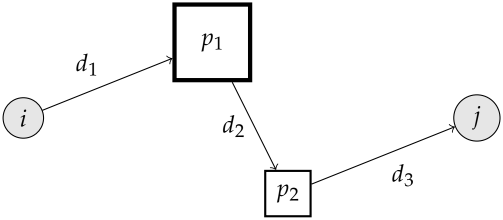

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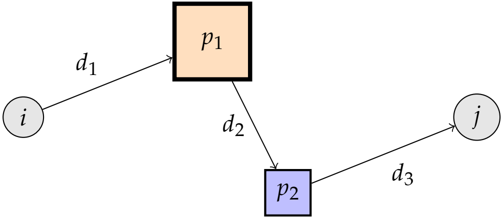
assumptions functional form



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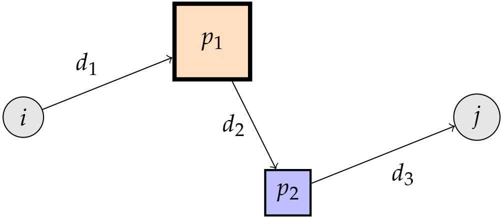

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$\rightarrow$ Firm's sourcing-routing decisions co-dependent with traffic congestion + affected by weather costs more

Model calibration

1. Recover elasticity of transportation costs to traffic Ξ_p, port capacity K_p, and weather risk ψ_p
    - Transportation costs = parametrized + estimated with microdata (firm-level trade + ports) estimation
    - Presence of congestion in traffic, scale economies in capacity, and climate trade costs

2. Baseline calibration: global economy, early 2000's
    - Weather conditions around ports = present climate (1980-2015) data
    - Geography (fundamentals) = sub-national level + matches local GDP estimates calibration model fit

Counterfactual

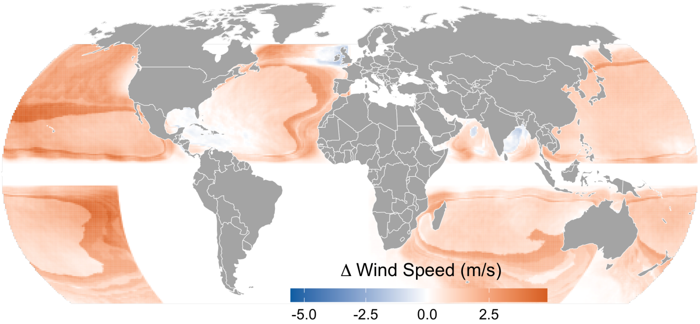

Figure 4: Present to RCP8.5 (2015-2050): Δ Tropical Cyclone Windspeed

1. ↑↓ weather shocks to transportation → RCP8.5 CΔ
2. RCP8.5 + no rerouting → optimal routes fixed as baseline

Quantitative results (RCP8.5)

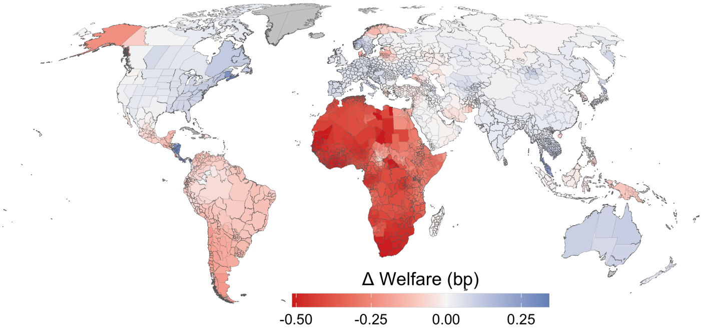

Figure 5: Δ Welfare (bp) - Present to RCP8.5 (2015-2050)

- Global welfare virtually non affected (+0.005 bp) but large spatial heterogeneity
- Δ global maritime traffic $\approx -0.26\%$

Quantitative results (RCP8.5 + fixed routing)

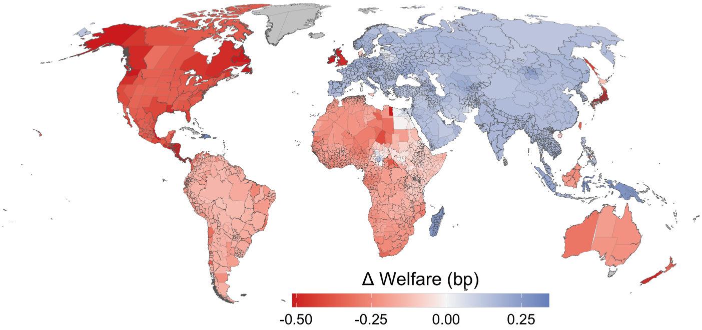

Figure 6: Δ Welfare (bp) without rerouting - Present to RCP8.5 (2015-2050)

- With no rerouting: Δ welfare ≈ −0.05 bp + spatial reallocation of welfare changes
- Δ global maritime traffic ≈ −4% port traffic

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Welfare gains from port investments

- Goal = quantify the welfare gains of port investments under CΔ + evaluate misallocation
- Sufficient statistics = Global welfare elasticity to port capacity K_p (model-based) more

$$\frac{\partial \log \bar{V}}{\partial \log K_p} = g(\underbrace{w_n}_{\text{wages}}, \underbrace{c_n}_{\text{factory costs}}, \underbrace{\Xi}_{\text{traffic}}; \underbrace{\psi}_{\text{climate}}) \quad (4)$$

- Account for:
  - income w_n + production cost c_n channels
  - traffic spillovers $\{\Xi_p\}_{p \in \mathcal{P}}$
  - weather at ports $\{\psi_p\}_{p \in \mathcal{P}}$
- Computable from standard trade/maritime traffic data + useful to guide investment in port capacity

First-order investment allocation

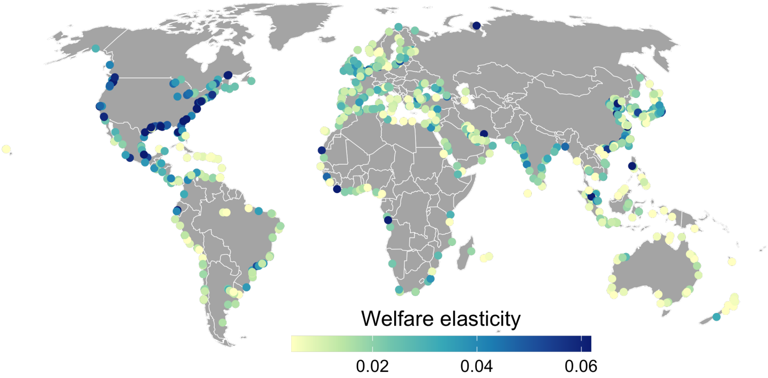
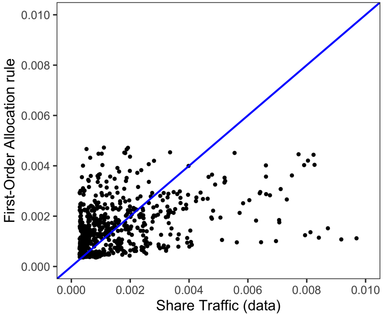


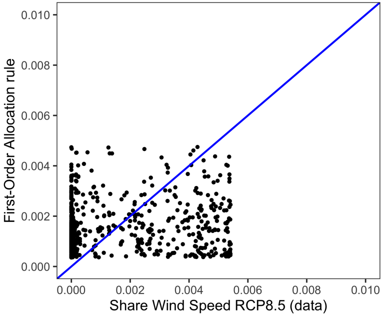
Figure 7: Global welfare elasticity (RCP8.5)

- First-order allocation rule: share of investment $\propto$ welfare elasticity

Evaluating port investments



(a) Allocation ∝ port traffic



(b) Allocation ∝ wind speed (RCP8.5)

- Misallocation of port investment under alternative rules:
  - Port traffic allocation rule = 43%
  - Weather risk allocation rule = 54%

Policy experiment: EU27

Conclusion

- Empirics: Firm-to-firm microdata + tropical cyclones

  $\rightarrow$ Exposure to cyclones diverts trade away from risky ports

- Quantification: spatial production networks + optimal routing

  $\rightarrow$ Rerouting = key adaptation margin, despite congestion spillovers

- Policy: Sufficient statistics = welfare gains of port improvements

  $\rightarrow$ Investments in trade infrastructure should take into account future climate damage + adaptation

Thank you!

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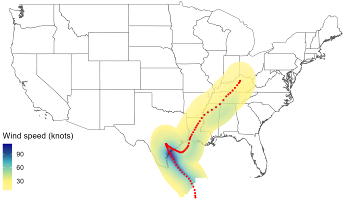
The case of Houston & Harvey (2017)

intro

- Category 4 Hurricane Harvey hits Texas in August 2017
  - Major seaports affected, including Houston (1 week ≈ 2.5 billion USD in transactions)
  - Port of Houston: 1 week closure + 1 month partial operations

- Spillover effects of disrupted transportation
  - Rail/road traffic rerouted from entering the Houston region
  - Tightened cargo capacity, increased freight rates, traffic congestion, shipment delays (≈ 2-3 days)



(a) Wind profile of hurricane Harvey (Aug. 2017).

(b) Flooded facilities, port of Houston

Climate change & tropical cyclone activity (US)

back

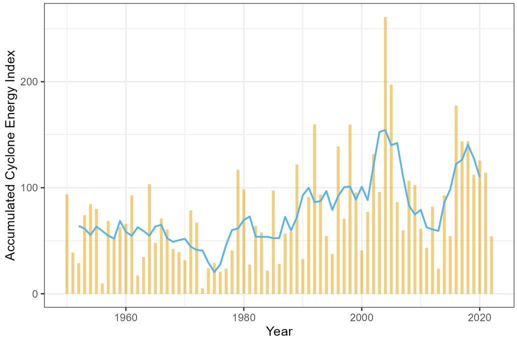
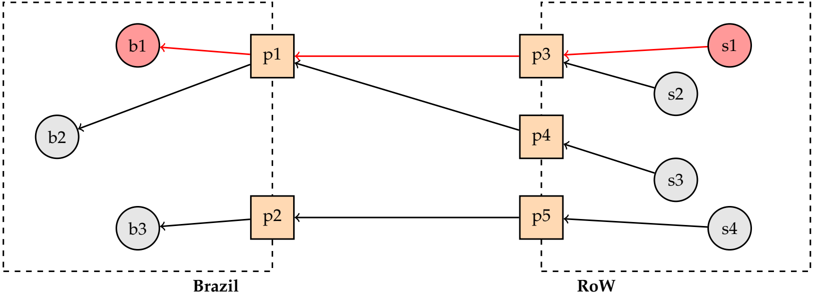


Figure 10: Annual cyclone activity (ACE) around US shores[1]

- Recent increasing trend in tropical cyclone activity in the US → undetermined relationship with CC
- Tropical cyclone intensity & rainfall rates will increase with CC → medium to high confidence

[1] Blue line = 5-year moving average

Bill of lading data back sample



Brazil (2014-2023) $\rightarrow$ near-universe of maritime imports (S&P Panjiva) $\approx$ 9M shipments

- Origin/destination establishments, origin/destination ports, weight (kg), volume (TEU)
- Restrict attention to geocoded establishments & ports, real cargo owners, frequent relationships

Tropical cyclones as weather shocks back

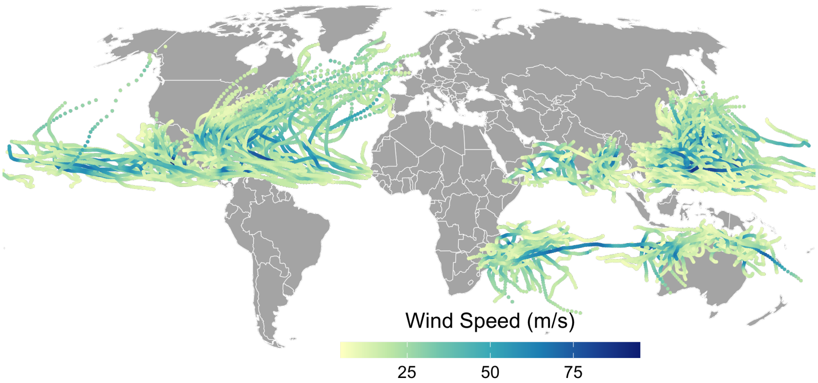


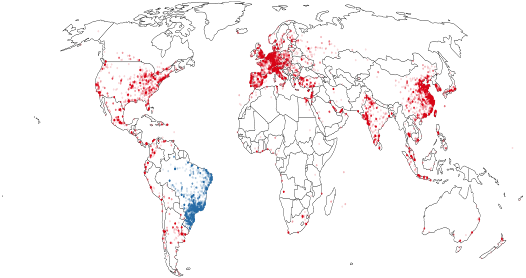
Figure 11: Tropical Cyclone Paths (IBTRACS) - 2014 to 2023

- Sample: 535 tropical cyclones, 310 ports exposed at least once
- Brazil is not exposed to tropical cyclones → weather shock = port of origin weather shocks

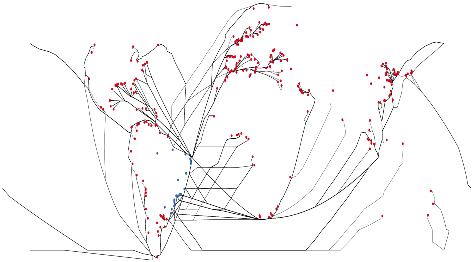
Firms, ports and routes

Data firms · Data routes · Sum. buyers · Sum. rel. · back

Final sample ≈ 1M shipments, from 23k suppliers, to 18k buyers, through 2k maritime routes



(a) Location of trading firms



(b) Maritime routes

Cyclone profiles Houston 2017 back

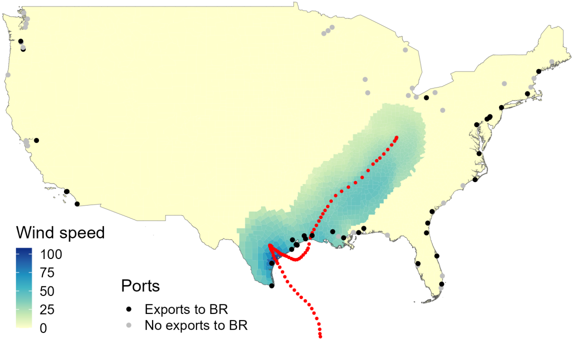


Figure 13: Example - Hurricane Harvey (Aug. 2017)

- Parametric modeling of cyclone wind profiles (Chen 1994; Willoughby et al. 2006) (IBTrACS data)

Tropical cyclones & climate change

back

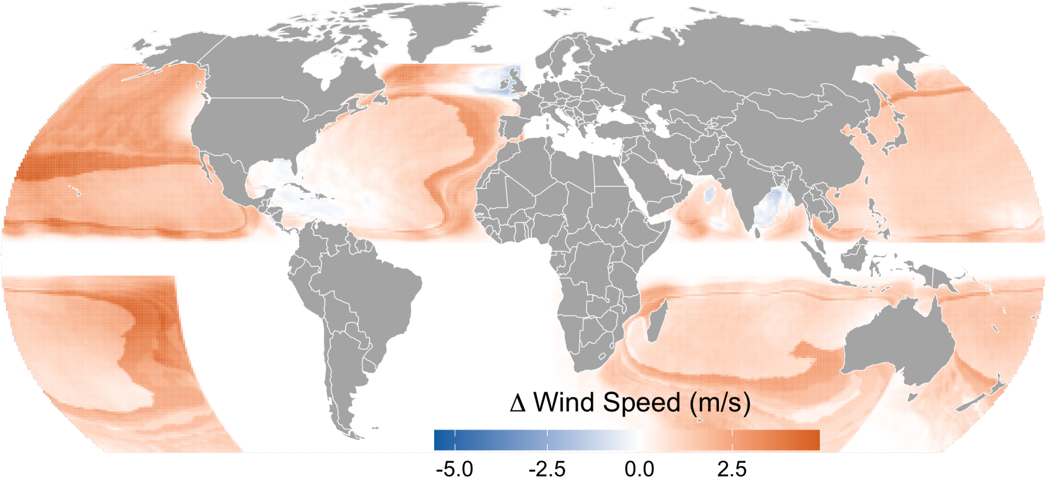


Figure 14: Present to RCP8.5 (2050): Δ Tropical Cyclone Windspeed

Tropical cyclone climate (1980-2015) data calibration

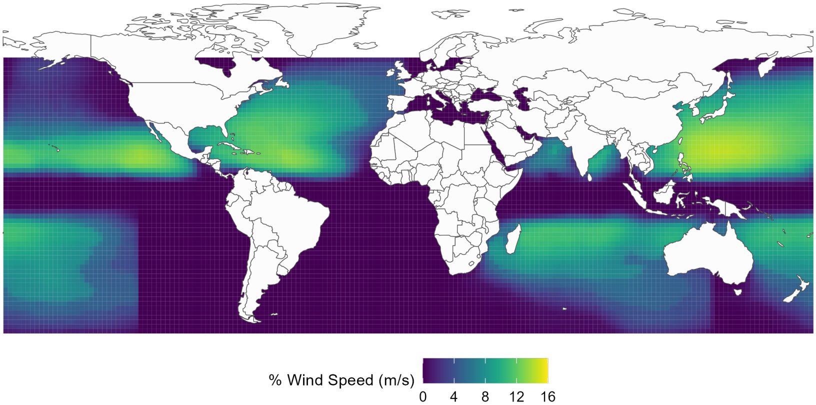


Figure 15: Present climate (1980-2015): Tropical Cyclone Windspeed

Data cleaning - firms

back

Table 1: Data Cleaning - Firms and Relationships

	Desc.	Num. Shipments	Num. Importers	Num. Exporters	Num. Rel.
Full Sample					
(1)	Raw Panjiva	9017154	44556	37973	185708
(2)	Drop missing parent company ID	8950897	44509	37868	185355
(3)	Drop poorly geolocalized firms	2205290	27136	31537	126811
(4)	Drop poorly reported ports	2204392	27133	31526	126754
(5)	Keep Brazilian imp., foreign exp.	2197635	26876	31027	125636
(6)	Drop NVO/forwarders	1039012	17692	23291	73551
Estimation Sample					
(7)	Drop infrequent rel.	994069	10787	13813	38665
(8)	Drop infrequent rel.-routes	938570	9748	12500	33304

Note: This table reports the effect of the data cleaning procedure on firm-related variables. Firms refer to geolocalized establishments. "Num. Shipments" refers to the number of distinct shipments, as identified by the bill of lading ID. "Num. Importers" refers to the number of establishments importing goods. "Num. Exporters" refers to the number of establishments exporting goods. "Num. Rel." refers to the number of trading establishment pairs.

Data cleaning - routes back

Table 2: Data Cleaning - Maritime Ports and Routes

	Desc.	Num. Exit Ports	Num. Entry Ports	Num. Routes	Num. Rel.-Routes
Full Sample					
(1)	Raw Panjiva	1005	52	5877	576861
(2)	Drop missing parent company ID	963	52	5430	572937
(3)	Drop poorly geolocalized firms	483	44	2011	242377
(4)	Drop poorly reported ports	474	43	1970	242005
(5)	Keep Brazilian imp., foreign exp.	467	43	1950	240440
(6)	Drop NVO/forwarders	442	42	1822	126684
Estimation Sample					
(7)	Drop infrequent rel.	366	37	1493	91046
(8)	Drop infrequent rel.-routes	247	35	1000	50932

Note: This table reports the effect of the data cleaning procedure on route-related variables. Routes refer to port of exit-port of entry pairs. ”Num. Exit Ports” refers to the number of port of lading, as identified by the UN/LOCODE. ”Num. Entry Ports” refers to the number of port of unlading, as identified by UN/LOCODE. ”Num. Routes” refers to the number of observed port pairs. ”Num. Rel.Routes” refers to the number of importer-exporter-route triplets.

Summary statistics - U.S. ports

back

Table 3: Summary Statistics - U.S. Ports Exporting to Brazil (per day)

Desc.	Mean	10%	25%	50%	75%	90%
Num. vessels	4.60	1.00	2.00	3.00	7.00	10.00
Num. shipments	214.47	2.00	4.00	56.00	323.00	652.00
Num. exporters	89.09	1.00	2.00	27.00	148.00	272.00
Log volume (TEU)	6.53	4.70	5.72	6.72	7.61	8.13
Log value (USD)	16.76	14.65	15.87	16.95	17.82	18.93

Summary statistics - Tropical cyclones back

Table 4: Summary Statistics - Tropical Cyclones

Desc.	Mean	10%	25%	50%	75%	90%
Per Tropical Cyclone Event						
Num. ports of lading	8.14	1.00	2.00	3.00	10.00	24.00
Windspeed (knots)	49.88	37.00	40.47	47.28	55.88	65.62
Exposure - 34 knots (hours)	11.12	4.20	6.66	9.41	13.80	19.88
Per Port - Year						
Num. cyclones	1.72	1.00	1.00	1.00	2.00	3.00
Windspeed (knots)	52.43	37.19	41.91	49.71	59.08	71.79
Exposure - 34 knots (hours)	12.38	3.78	6.86	10.22	16.10	24.78

Summary statistics - Buyers back

Table 5: Summary Statistics - Relationship Sample

Desc.	Mean	25%	50%	75%	90%	95%
Per Buyer - Month						
Num. transactions	6.20	1.00	2.00	4.00	10.00	19.00
Num. suppliers	1.71	1.00	1.00	2.00	3.00	4.00
Num. exit ports	1.73	1.00	1.00	2.00	3.00	5.00
Num. entry ports	1.13	1.00	1.00	1.00	1.00	2.00
Num. routes	1.78	1.00	1.00	2.00	3.00	5.00
Log weight (kg)	11.01	9.93	10.80	11.99	13.22	14.13
Log volume (TEU)	1.58	0.69	1.39	2.48	3.53	4.23
Log value (USD)	12.12	11.02	11.94	13.06	14.22	15.01

Summary statistics - Relationships

back

Table 6: Summary Statistics - Relationship Sample

Desc.	Mean	25%	50%	75%	90%	95%
Per Relationship - Month						
Num. transactions	3.62	1.00	1.00	2.00	5.00	10.00
Num. exit ports	1.15	1.00	1.00	1.00	2.00	2.00
Num. entry ports	1.04	1.00	1.00	1.00	1.00	1.00
Num. routes	1.18	1.00	1.00	1.00	2.00	2.00
Log weight (kg)	10.57	9.77	10.34	11.46	12.55	13.34
Log volume (TEU)	1.23	0.69	0.69	1.95	2.94	3.58
Log value (USD)	11.79	10.85	11.63	12.61	13.68	14.42

Port disruptions back

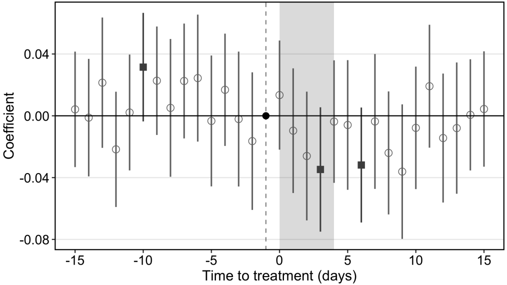
$$y_{p,t,\tau} = \sum_{h=-15}^{15} \beta_h E_{p,\tau} + \alpha_{p,\tau} + \alpha_{t,\tau} + \varepsilon_{p,t,\tau}$$

- $y_{p,t,\tau}$ is the outcome at the port level (daily), for cyclone event τ
  - port activity = 1 if $\#\text{vessels}_{p,t,\tau} > 0$, 0 otherwise
  - $\log(\#\text{vessels}_{p,t,\tau})$, conditioning on port activity
- $E_{p,\tau} = 1$ if port p exposed to cyclone at time τ
- Non-absorbing treatments with a 15-day stabilization period

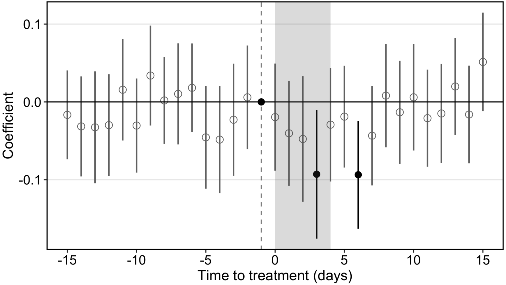
Exposure to tropical cyclone - placebo back

Exposure to tropical cyclones with weak winds ($\leq$ 18m/s)

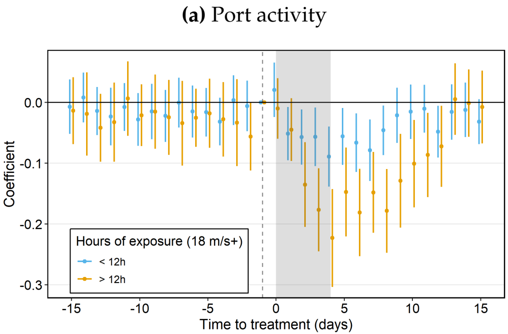
(a) Port activity

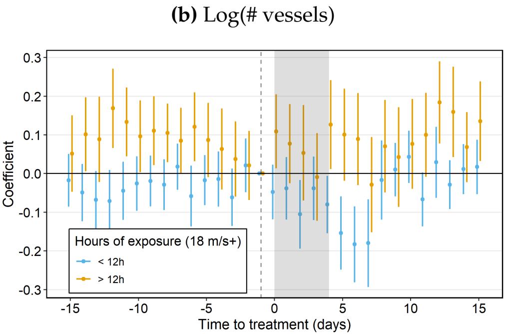


(b) Log(# vessels)



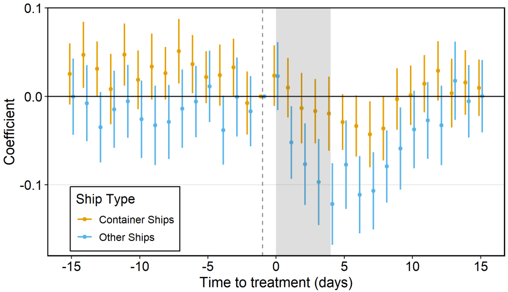
Exposure to tropical cyclone - het. in exposure time back



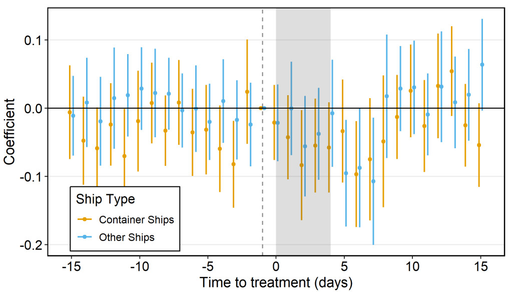


Exposure to tropical cyclone - het. in containerization back

(a) Port activity



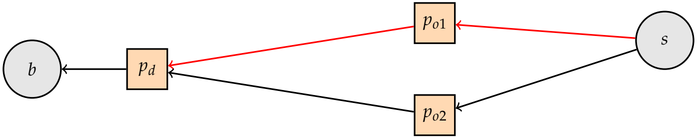
(b) Log(# vessels)



Routing disruptions (back)

$$y_{bsr,t,\tau} = \sum_{h=-6}^{h=12} \left[\beta_h E_{p_o,\tau} + \delta_h X_{bsr,h,\tau} + \alpha_{h,\tau} \right] + \alpha_{bsr,\tau} + \alpha_{bs,t} + \varepsilon_{bsr,t,\tau}$$

- $y_{bsr,t,\tau}$ is the outcome of buyer-supplier-route $\{b, s, \overbrace{p_o, p_d}^{\text{route} = r}\}$, for cyclone event τ
  - activity = 1 if $\#\text{shipments}_{bsr,t,\tau} > 0$, 0 otherwise (conditioned on b & s entry)
  - intensive margins: $\log(\#\text{shipments}_{bsr,t,\tau})$, $\log(\text{weight}_{bsr,t,\tau})$, $\log(\text{volume}_{bsr,t,\tau})$
- $X_{bsr,h,\tau}$ = pre-shock route characteristics: frequency, # shipments, timing of last shipment
- Non-absorbing treatment exposure $E_{p_o,\tau}$ with no overlaps (6m)
- Variation: within relationships $\{b, s\}$, across ports of origin p_o, for routes active before τ (6m)



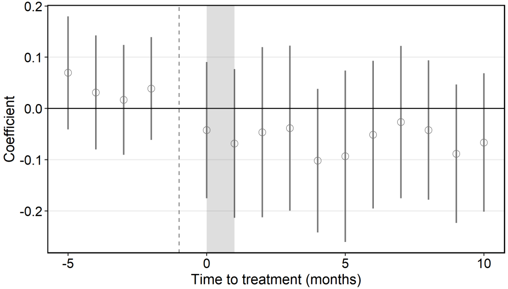
Sourcing disruptions back

$$y_{bs,t,\tau} = \sum_{h=-6}^{h=12} \left[\beta_h E_{p_o,\tau} + \delta_h X_{bs,h,\tau} + \alpha_{h,\tau}\right] + \alpha_{bs,\tau} + \alpha_{b,t} + \alpha_{s,t} + \varepsilon_{bsr,t,\tau}$$

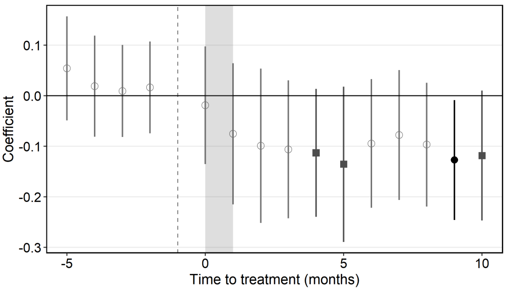
- $y_{bs,t,\tau}$ is the outcome of buyer-supplier $\{b,s\}$, for cyclone event τ
  - activity = 1 if #shipments$_{bs,t,\tau} > 0$, 0 otherwise (conditioned on b & s entry)
  - intensive margins: $\log(\#\text{shipments}_{bs,t,\tau})$, $\log(\text{weight}_{bs,t,\tau})$, $\log(\text{volume}_{bs,t,\tau})$
- $X_{bs,h,\tau}$ = pre-shock relationship characteristics: frequency, # shipments, timing of last shipment
- Non-absorbing treatment exposure $E_{p_o,\tau}$ with no overlaps (6m)
- Variation: within buyers, across suppliers, for rel. active before τ (6m)

Route choice - intensive margins back

(a) Log volume (TEU)

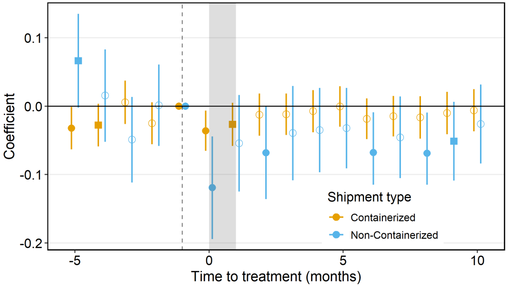


(b) Log # shipments

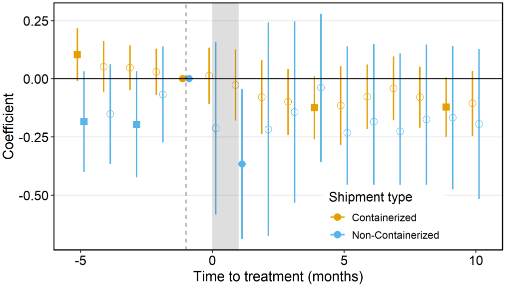


Route choice - containerized goods back

(a) Route activity (containers vs. bulk)



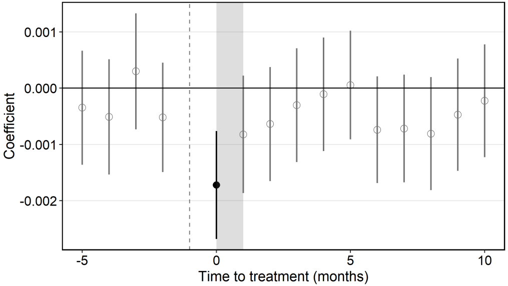
(b) Log shipments (containers vs. bulk)



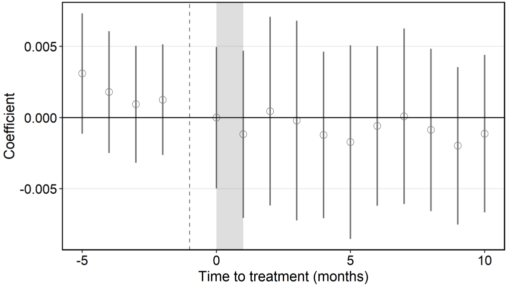
Route choice - windspeed back

Continuous treatment = wind speed (m/s)

(a) Route activity (continuous treatment)



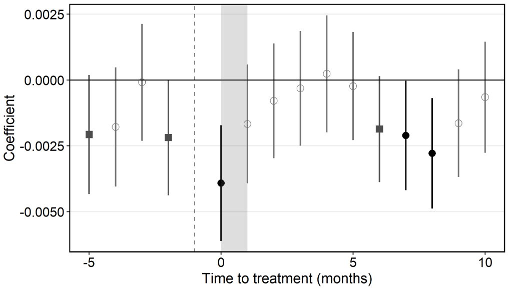
(b) Log weight (kg) (continuous treatment)



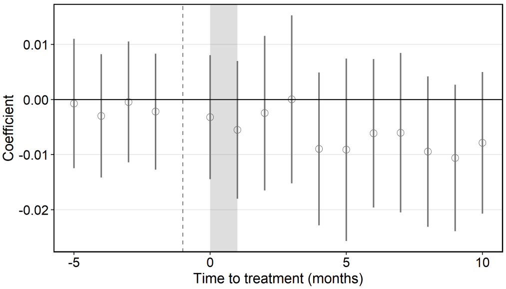
Route choice - exposure back

Continuous treatment = exposure to $\geq$ 18 m/s (hours)

(a) Route activity (continuous treatment)



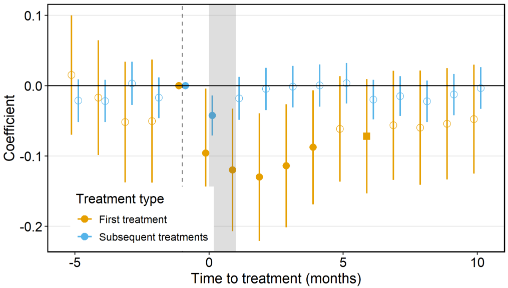
(b) Log weight (kg) (continuous treatment)



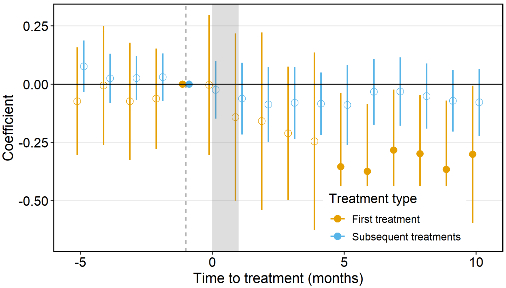
Route choice - 1^{st} vs. n^{th} treatment

back

(a) Route activity (1^{st} vs. n^{th} treatment)



(b) Log shipments (1^{st} vs. n^{th} treatment)

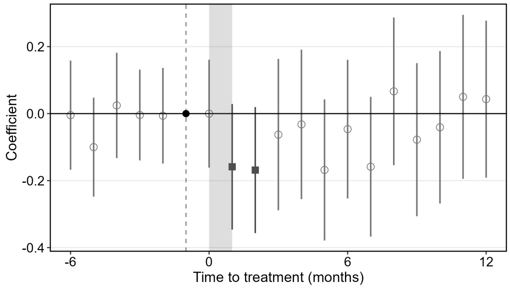


Route choice - aggregate effect back

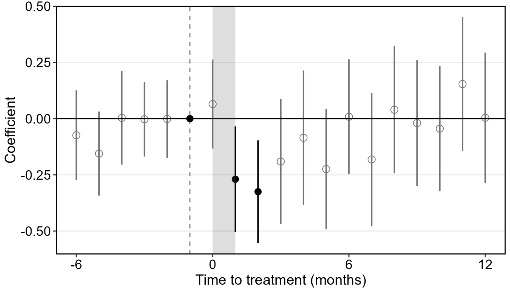
$$y_{n_o,p_o,t,\tau} = \sum_{h=-6}^{h=12} \left[\beta_h E_{p_o,\tau} + \alpha_{h,\tau}\right] + \alpha_{n_o,p_o,\tau} + \alpha_{n_o,t} + \varepsilon_{n_o,p_o,t,\tau}$$

- $y_{n_o,p_o,t,\tau}$ is the outcome at the origin-port level $\{n_o, p_o\}$, for cyclone event τ
- Variation: within origin location (GAUL1) n_o, across ports of origin p_o

(a) Log # shipments

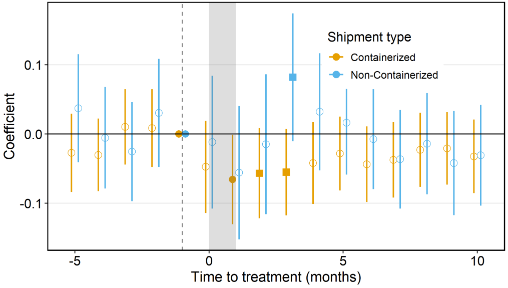


(b) Log volume (TEU)

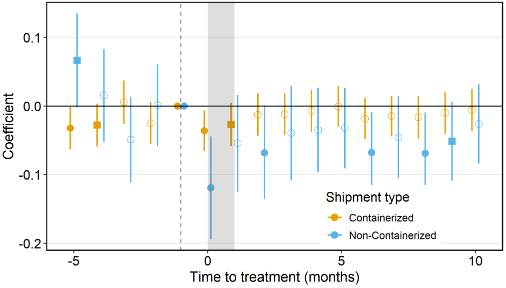


The role of rerouting frictions (back)

(a) Relationship activity (containers vs. bulk)



(b) Route activity (containers vs. bulk)

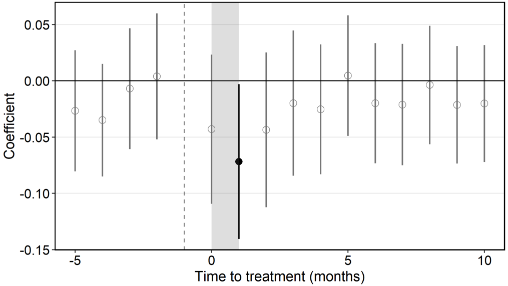


- Containerized shipping → predetermined lines, fixed schedules
- ↑ firm-to-firm disruptions when rerouting is limited!

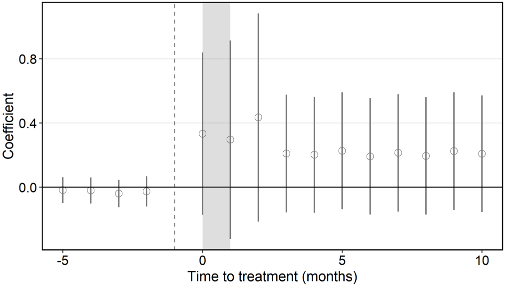
Firm-to-firm - exposure back

Continuous treatment = share of shipments exposed to tropical cyclones

(a) Relationship activity (continuous treatment)

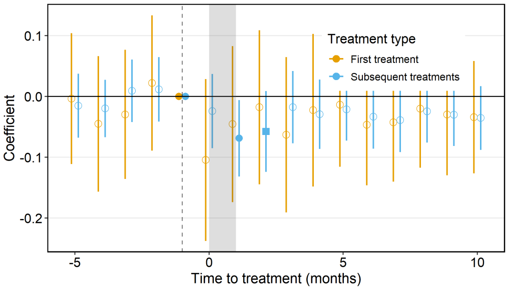


(b) Log weight (continuous treatment)

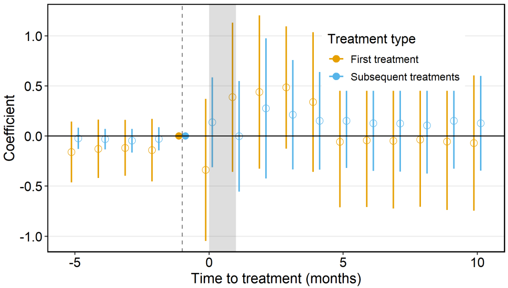


Firm-to-firm - 1^{st} vs. n^{th} treatment back

(a) Relationship activity (1^{st} vs. n^{th} treatment)



(b) Log weight (1^{st} vs. n^{th} treatment)



Port condition ZULU

back

Marine Safety Information Bulletin

Commander
U.S. Coast Guard
Sector Key West
100 Trumbo Road
Key West, FL 33040-6655

MSIB Number: SKW-28-24
Date: Oct 7, 2024
Contact: LT Hailye Wilson
Phone: (305) 292-8768
Email: SKWWaterways@uscg.mil

U.S. COAST GUARD SECTOR KEY WEST PORT CONDITION ZULU

On October 8, 2024, at 0600 (6:00 AM), the Captain of the Port will set Port Condition (PORTCON) ZULU for the Port of Key West. The shift is based on the projected arrival of sustained gale force winds (greater than 34 knots/39mph) associated with Hurricane Milton. The table below summarizes COTP requirements for PORTCON Zulu in accordance with 33 CFR 165.707:

Hours Prior to Gales	Port Condition	Requirements *(annotated from 33 CFR 165.707)*
72	Whiskey	• Oceangoing vessels greater than 300 gross tons (GT) must make plans to depart no later than the setting of Port Condition Yankee unless authorized by the COTP. Vessels intending to remain in port must contact the COTP prior to setting PORTCON X-Ray.
48	X-Ray	• Vessels greater than 300 GT without an approval to remain in port must depart prior to the setting of PORTCON Yankee. • All vessels, regulated facilities, and waterfront facilities must ensure that potential flying debris is removed or secured. HAZMAT/pollution hazards must be secured in a safe manner away from waterfront areas.
24	Yankee	• The port is closed to all inbound vessel traffic. All vessels greater than 300 GT must have departed the port, unless authorized by the COTP.
12	Zulu	• The port is closed to all vessel traffic except as specifically authorized by the COTP. • Regulated facilities must cease all cargo operations, including bunkering and lightering.
After Storm's Passage	Four *(All Clear)*	• The port will be re-opened only after satisfactory assessments of the waterways, including critical aids to navigation verifications, have been conducted.

Functional form assumptions: productivity firms

Assumption

For any firm i in region n, the number of potential suppliers $j \in M_{n'}$ from which i can draw a match with productivity $z > \bar{z}$ follows a Poisson distribution with mean $a_{n'}\bar{z}^{-\xi}$, where $a_{n'}$ is the fundamental productivity of firms in region n'.

Functional form assumptions: weather costs shipping

Assumption

Port-level wedges are randomly drawn from a Pareto distribution with c.d.f. $F_{p(r)}(\theta) = 1 - \theta^{-\psi_{p(r)}}$, *for* $\theta_{p(r)} \geq 1$.

Sourcing & routing in equilibrium back

- Route-level bilateral trade shares:

$$\pi_{n',r} = \frac{a_n \cdot \bar{c}_n^{-\xi} \cdot \tau_{nn'}(r)^{-\xi}}{\sum_{\tilde{n}} a_{\tilde{n}} \cdot \bar{c}_{\tilde{n}}^{-\xi} \cdot \sum_{r \in \mathcal{R}_{\tilde{n}n'}} \tau_{\tilde{n}n'}(r)^{-\xi}} \tag{5}$$

- Probability that firms in n' supply from n through route r sourcing shares factory-gate costs

Sourcing & routing in equilibrium back

- Route-level bilateral trade shares:

$$\pi_{n',r} = \frac{a_n \cdot \bar{c}_n^{-\xi} \cdot \tau_{nn'}(r)^{-\xi}}{\sum_{\tilde{n}} a_{\tilde{n}} \cdot \bar{c}_{\tilde{n}}^{-\xi} \cdot \sum_{r \in \mathcal{R}_{\tilde{n}n'}} \tau_{\tilde{n}n'}(r)^{-\xi}} \tag{5}$$

- Probability that firms in n' supply from n through route r sourcing shares factory-gate costs

- Route-level transportation costs $\tau_{nn'}(r)^{-\xi}$ (parametrized): functional form

$$\tau_{nn'}(r)^{-\xi} = \underbrace{\left(\prod_{k=1}^{|\mathcal{B}_r|} \epsilon_{r_{k-1},r_k}^{\lambda_1}\right)}_{\text{leg-level costs}} \cdot \underbrace{\left(\prod_{m=1}^{|\mathcal{P}_r|} \Xi_{p(r)_m}^{\lambda_2} \cdot K_{p(r)_m}^{\lambda_3} \cdot \frac{\psi_{p(r)_m}}{\psi_{p(r)_m} + \xi}\right)}_{\text{port } \times \text{ weather costs}} \tag{6}$$

→ Firm's sourcing-routing decisions are co-dependent with traffic congestion + affected by weather costs

Traffic in equilibrium back

- Summing trade volumes $\times$ probability of using port $p \rightarrow$ equilibrium port traffic

$$\Xi_p = \sum_n \sum_{n'} \left(\tau_{np} \tau_{pn'} \tau_{nn'}^{-1} \right)^{-\xi} X_{nn'} \tag{7}$$

  - $X_{nn'}$ = trade volumes from n to n'
  - $\tau_{nn'}$ = average cost to ship from n' to n accounting for all possible routes
  - $\left(\tau_{np} \tau_{pn'} \tau_{nn'}^{-1} \right)^{-\xi}$ = probability (n, n') use port p

$\rightarrow$ Traffic = spillover $\rightarrow$ inefficient equilibrium

Sourcing decisions back

- Region-level bilateral trade shares:

$$\pi_{nn'} = \frac{M_n \cdot \bar{c}_n^{-\xi} \cdot \tau_{nn'}^{-\xi}}{\sum_{\tilde{n}} M_{\tilde{n}} \cdot \bar{c}_{\tilde{n}}^{-\xi} \cdot \tau_{\tilde{n}n'}^{-\xi}} \tag{8}$$

- Factory-gate cost indices $\bar{c}_n$ interlinked through production network structure factory-gate costs

- Optimal transportation costs $\tau_{nn'}$ given by

$$\tau_{nn'}^{-\xi} = \sum_{r \in \mathcal{R}_{nn'}} \underbrace{\left(\prod_{k=1}^{|\mathcal{B}_r|} d(\epsilon_{r_{k-1}, r_k})^{-\xi} \right)}_{\text{leg-level costs}} \underbrace{\left(\prod_{m=1}^{|\mathcal{P}_r|} t(\Xi, K_p)^{-\xi} \cdot \frac{\psi_p}{\psi_p + \xi} \right)}_{\text{port} \times \text{weather costs}} \tag{9}$$

Factory-gate costs back

The marginal cost distribution of firms in $M_{n'}$ is Weibull:

$$P(c_i(\phi, r) > c) = exp\left[-\left(a_n w_{n'}^{\alpha-1}\right)^{\frac{\xi}{\alpha}}\left(\sum_n a_n \bar{c}_n^{-\xi} \sum_{r\in\mathcal{R}_{nn'}} \prod_{k=1}^{|\mathcal{B}_r|} d_{r_{k-1},r_k}^{-\xi} \prod_{m=1}^{|\mathcal{P}_r|} \bar{t}_{p(r)_m}^{-\xi}\right) c^{\frac{\xi}{\alpha}}\right] \tag{10}$$

$$\text{where} \quad \bar{c}_n^{-\xi} = a_n^{\xi} w_n^{(\alpha-1)\xi} \left(\sum_{\tilde{n}} a_{\tilde{n}} \bar{c}_{\tilde{n}}^{-\xi} \sum_{r\in\mathcal{R}_{\tilde{n}n}} \prod_{k=1}^{|\mathcal{B}_r|} d_{r_{k-1},r_k}^{-\xi} \prod_{m=1}^{|\mathcal{P}_r|} \bar{t}_{p(r)_m}^{-\xi}\right)^{\alpha} \Gamma(1-\alpha) \tag{11}$$

Transportation costs - functional form (shipping) (sourcing-routing) (traffic)

Transportation costs:

$$d_{nn'}^{-\xi} = \epsilon_{nn'}^{\lambda_1}, \text{ and } \quad \bar{t}_p^{-\xi} = \Xi_p^{\lambda_2} K_p^{\lambda_3} \frac{\psi_p}{\psi_p + \xi}, \tag{12}$$

where:

- λ_1 is the elasticity w.r.t. distance
- λ_2 is the elasticity w.r.t. port-level congestion
- λ_3 is the elasticity w.r.t. port-level capacity
- $\frac{\psi_p}{\psi_p+\xi}$ is the 1^{st} moment of the distribution of port-level weather costs $\theta_{p(r)_m}^{-\xi}$

Estimating transportation costs (back)

- Data (2019-2023, weekly) = bills of lading + daily port operations + cyclone risks

- Reduced-form analog to route-level bilateral trade shares:

$$\log(\pi^{value}_{n_d,r,t}) = \alpha_{n_o,t} + \alpha_{n_d,t} + \alpha_{p_d,t} + \alpha_1 \log(Distance_r) + \alpha_2 \log(\Xi^{TEU}_{p_o,t}) + \alpha_3 \log(K^{TEU}_{p_o}) + \alpha_4 \log(CycloneRisk_{p_o}) + \varepsilon_{n_d,r,t}. \quad (13)$$

- Endogeneity in port traffic & port capacity → geography-based instruments (instruments)

Estimating transportation costs back

- Data (2019-2023, weekly) = bills of lading + daily port operations + cyclone risks

- Reduced-form analog to route-level bilateral trade shares:

$$\log(\pi^{value}_{n_d,r,t}) = \alpha_{n_o,t} + \alpha_{n_d,t} + \alpha_{p_d,t} + \alpha_1 \log(Distance_r) + \alpha_2 \log(\Xi^{TEU}_{p_o,t}) + \alpha_3 \log(K^{TEU}_{p_o}) + \alpha_4 \log(CycloneRisk_{p_o}) + \varepsilon_{n_d,r,t}. \quad (13)$$

- Endogeneity in port traffic & port capacity → geography-based instruments instruments

- Key estimated parameters (2SLS): results
  - $\alpha_2 = -1.78$ → elasticity to traffic (congestion)
  - $\alpha_3 = 2.36$ → elasticity to port capacity (scale economies)
  - $\alpha_4 = -0.08$ → elasticity to expected tropical cyclone winds (climate risks)

Instrumenting port traffic & capacity back

- $z^1_{p,t}$ = instrument for port traffic

  $\rightarrow$ shift = global traffic $\times$ share = coastal population around port (1950)

- z^2_p = instrument for port capacity

  $\rightarrow$ mean terrain ruggedness around port

- First stage:

	Log Port Origin Traffic (1)	Log Port Origin Capacity (2)
$z^1_{p_o,t}$	0.59	0.47
	(0.00)	(0.00)
$z^2_{p_o}$	-0.44	-0.39
	(0.00)	(0.00)
Observations	141,086	141,117
Adjusted R^2	0.69	0.69
FE + controls	Yes	Yes

Transportation costs - results

back

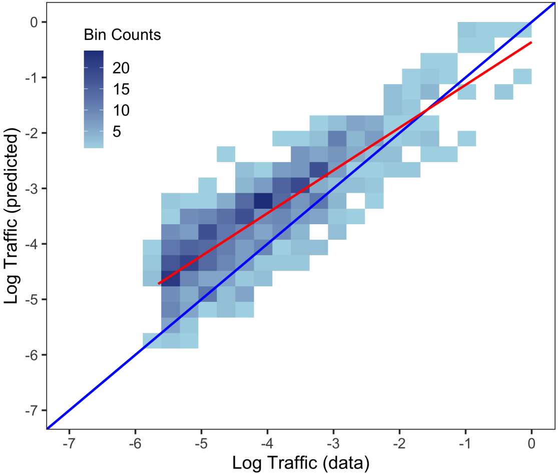
Table 7: Estimation of transportation costs

	$\pi^{value}_{n_d,r,t}$ (1)	(2)
Log Port Origin Traffic	-0.01	-1.78
	(0.03)	(0.25)
Log Port Origin Capacity	0.15	2.36
	(0.04)	(0.31)
Log Distance	-0.36	-0.46
	(0.03)	(0.04)
Log Cyclone Risk	-0.02	-0.08
	(0.01)	(0.01)
Observations	90,504	90,504
Adjusted R^2	0.67	0.64
Wald-F, Log Port Origin Traffic		9,476.47
Wald-F, Log Port Origin Capacity		9,453.84
n_d-week fixed effects	✓	✓
n_o-week fixed effects	✓	✓
p_d-week fixed effects	✓	✓

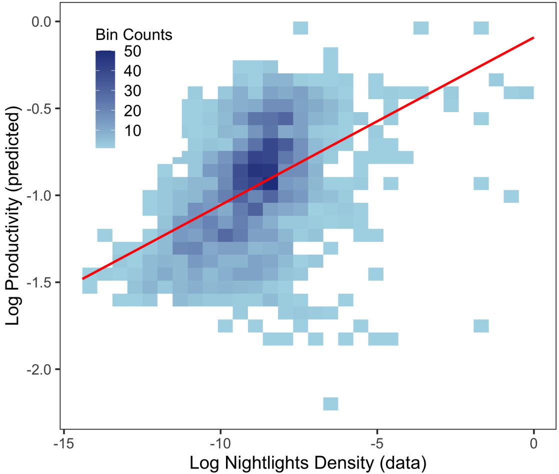
Model calibration back

Parameters	Description	Source/Procedure
Panel A: Parameters from related literature		
$\sigma = 2$	Final goods CES	Castro-Vincenzi et al. 2024
$\alpha = 0.8$	Intermediate input share	Balboni et al. 2024
$\xi = 8$	Trade elasticity	Ganapati et al. 2024
Panel B: Calibrated parameters		
$\lambda_1 = -0.5$	Distance elasticity	Estimated
$\lambda_2 = -1.8$	Traffic elasticity	Estimated
$\lambda_3 = 2.4$	Capacity elasticity	Estimated
Fundamentals	**Description**	**Source/Matched moments**
Panel C: Calibrated fundamentals		
$\mathcal{N}$	Regions	Aggregation at GAUL1 level
$\mathcal{P}$	Ports	IMF PortWatch
$\mathcal{L}$	Population	Rossi-Hansberg et al. 2025
$\mathcal{A}$	Region-level productivity	Matched to Rossi-Hansberg et al. 2025
$\mathcal{D}$	Distance	Eurostat SeaRoute & OpenStreetMap
$\mathcal{K}$	Port capacity	IMF PortWatch
ψ	Cyclone risk	STORM

Model fit back



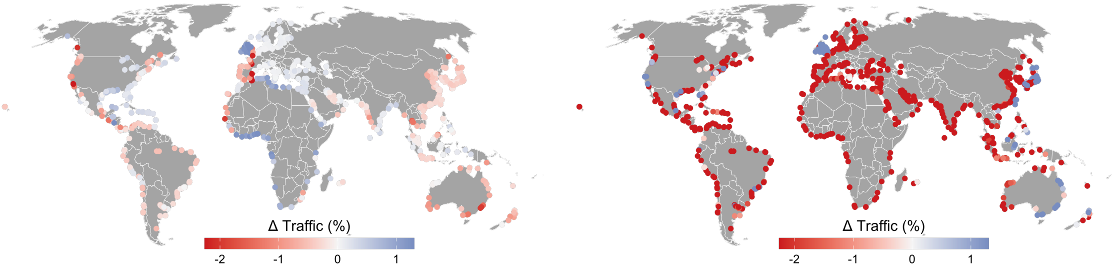
(a) Port Traffic (Untargeted)



(b) Nightlights (Untargeted)

Quantitative results - port traffic

back



(a) Δ Port traffic (%)

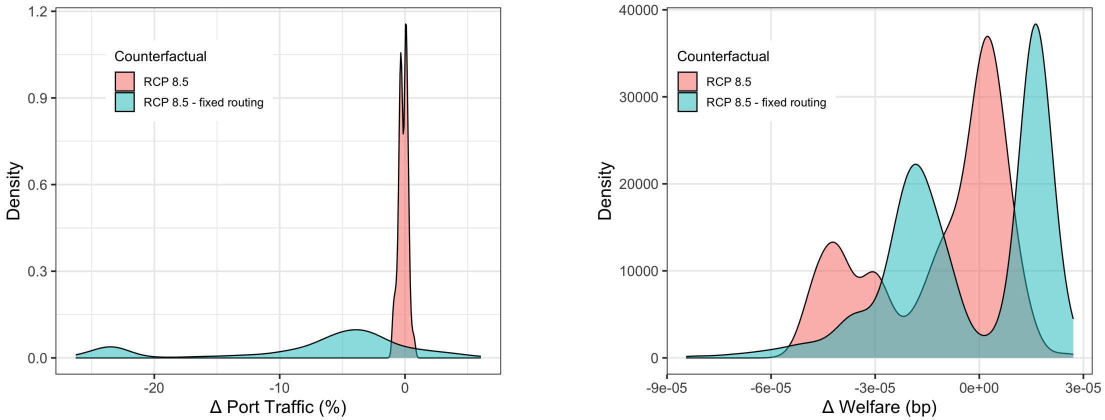
(b) Δ Port traffic (%) - fixed routing

Figure 29: Quantitative results - Present to RCP8.5 (2015-2050)

- Without rerouting as adaptation = larger decline in port traffic + decorrelation from weather risks

rerouting results

Re-routing as adaptation back



- Re-routing = lower heterogeneity in Δ traffic + halved welfare losses

Welfare elasticity to port capacity (back)

The elasticity of global welfare $\bar{V} = \sum_n V_n$ with respect to port capacity K_p is given by:

$$\frac{\partial \log \bar{V}}{\partial \log K_p} = \sum_n \frac{V_n}{\bar{V}} \left[\beta_w g^{(w)}_{n,p} + \beta_\tau \sum_{n'} \pi_{n'n} \left[-\xi g^{(c)}_{n',p} + \lambda_3 \Theta_{p|nn'} + \lambda_2 \sum_{p' \in \mathcal{P}} \Theta_{p'|nn'} g^{(\Xi)}_{p',p} \right] \right], \tag{14}$$

where $g^{(w)}_{n,p} = \frac{\partial \log w_n}{\partial \log K_p}$, $g^{(c)}_{n,p} = \frac{\partial \log \bar{c}_n}{\partial \log K_p}$, and $g^{(\Xi)}_{p',p} = \frac{\partial \log \Xi_{p'}}{\partial \log K_p}$, and β_w and β_τ are constants built from economy-wide parameters. The elasticities to wages, factory-gate costs, and port traffic to port capacity are the solution to the following set of equations:

$$\begin{bmatrix} \mathbf{A}_{ww} & \mathbf{A}_{w\Xi} & \mathbf{A}_{wc} \\ \mathbf{A}_{\Xi w} & \mathbf{A}_{\Xi\Xi} & \mathbf{A}_{\Xi c} \\ \mathbf{A}_{cw} & \mathbf{A}_{\Xi c} & \mathbf{A}_{cc} \end{bmatrix} \begin{bmatrix} \frac{\partial \log w_n}{\partial \log K_p} \\ \frac{\partial \log \Xi_p}{\partial \log K_p} \\ \frac{\partial \log \bar{c}_n}{\partial \log K_p} \end{bmatrix} = \begin{bmatrix} b_w \\ b_\Xi \\ b_c \end{bmatrix}, \tag{15}$$

where

$$\{\mathbf{A}_{ww}, \mathbf{A}_{w\Xi}, \mathbf{A}_{wc}, \mathbf{A}_{\Xi w}, \mathbf{A}_{\Xi\Xi}, \mathbf{A}_{\Xi c}, \mathbf{A}_{cw}, \mathbf{A}_{\Xi c}, \mathbf{A}_{cc}, b_w, b_\Xi, b_c\}$$

are constants built from equilibrium objects.

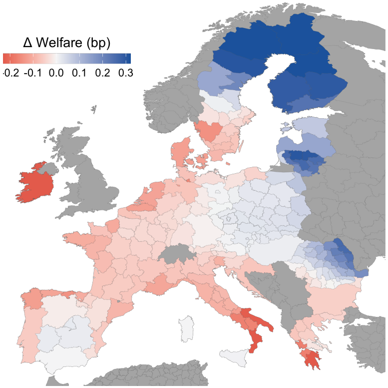
Policy experiment - EU27 port investments back

- EU27 plan about USD 93 billion of port-level investments by 2034 (ESPO 2024)

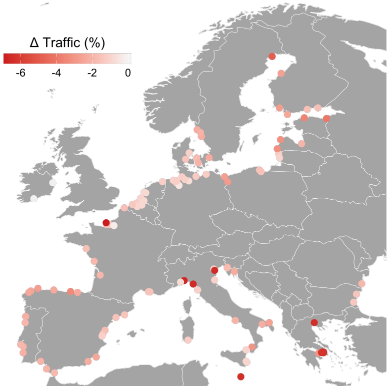
- Need to translate USD of investment into port capacity
  - Data = World Bank PPI projects + daily port operations (2019-2023) more
  - USD 1B of investment = 27% increase in port capacity

- EU27 first-order allocation rule: with and without RCP8.5 climate risks more

Policy experiment - results back



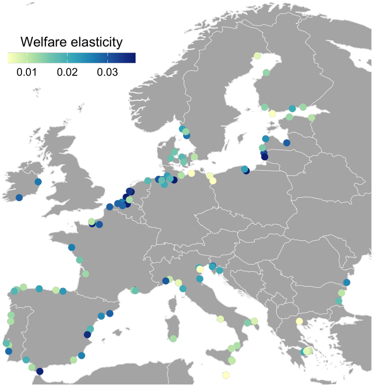
(a) Δ Welfare (bp)



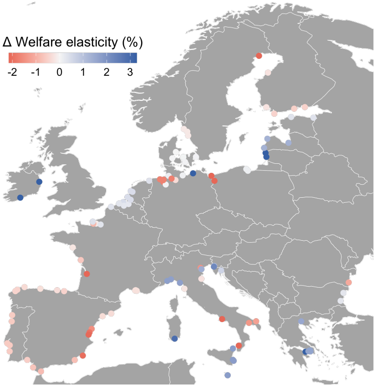
(b) Δ Port traffic (%)

- Misallocation of EU27 port investment = 0.5%
- Economic impact: Δ welfare = -0.04 bp, Δ port traffic = -1.6%

EU27 first order allocation rule back



(a) EU27 welfare elasticity (RCP8.5)



(b) Δ EU27 welfare elasticity (%)

Elasticity of port capacity to investment back

$$K_{p,t} = \sum_{\substack{k \in \mathcal{K} \\ k \neq -1}} \beta_k \mathbf{1}\{\tau_{p,t} = k\}\, I_p + \alpha_p + \gamma_{t \times q_{p,t}} + \varepsilon_{p,t}, \tag{16}$$

where

- $K_{p,t}$ is port capacity at year t
- $\tau_{p,t}$ is the year of investment
- I_p is the invested amount (billions of USD)

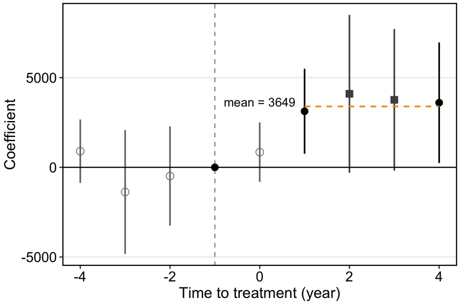


Figure 33: Port capacity - LMIC ports