Weathering the Storm: Supply Chains and Climate Risk

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Motivation

- Rise of complex supply chains:
  - Key feature of recent globalization: Efficiency gains from specialization in production.
  - But, can propagate and amplify economic shocks.
- Supply chain disruptions (e.g. Covid lockdowns, port bottlenecks, floods) can create supply shortages and inflationary pressures.

Motivation

- Rise of complex supply chains:
  - Key feature of recent globalization: Efficiency gains from specialization in production.
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- Supply chain disruptions (e.g. Covid lockdowns, port bottlenecks, floods) can create supply shortages and inflationary pressures.
- Question: *How do firm supply chains adapt to risks e.g. climate risk?*
  - If climate risk anticipated, firm supply chains might already be adapted
  - More intensive margin adjustment/less extensive margin?
  - Larger/ more nodal firms better able to adapt to anticipated climate events?

This paper

1. Universe of firm-to-firm transactions for a large Indian state.
2. Event study: flooding events in India
3. Model: firm optimal sourcing under climate risk
4. Quantification
   - Calibrate to observed regions in India, infer regional risk probabilities

   Counterfactuals
   - Homogenous risk, regional autarky
   - (in progress) Do private firm resilience choices lead to resilient networks?

Preview of Results

- Event study: responses to climate shocks
  - Short decline in inputs
  - No change in suppliers
  - Suggests firms adapting to climate risk
- Spatial G.E. model of input sourcing under climate risk
  - Diversification through supply chains: firms trade-off input costs and sourcing risk
  - Less productive but less risky regions can see welfare gains
  - Trade vs autarky: real wages and volatility of real wages lower under costly trade
- Quantification
  - Inferred shock probabilities positively correlated with climate observables (correlations of 0.47-0.56)
  - Wages on average 9% smaller, variance 90% lower in baseline relative to autarky
  - Wages on average 11% smaller, variance 25% larger relative to free trade.

Related Literature

Production networks, shock transmission, and endogenous network formation

- Barrot and Sauvagnat (2016), Boehm et al (2019), Carvalho et al. (2021), Huneeus (2021), Dhyne et. al. (2021), Arkolakis et al (2023), Dhyne et. al. (2023).
- Contribution: new data+climate shocks + focus on intensive and extensive margins.

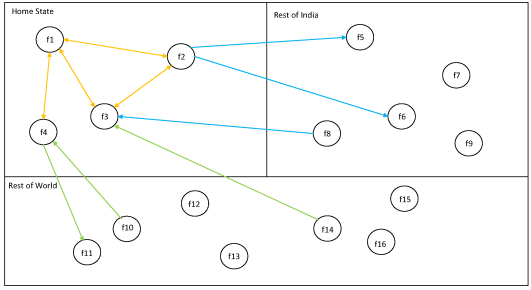
Firm/Supply Chain adaptation to climate risk

- Castro-Vincenzi (2022), Balboni et al (2023)
- Contribution: emphasis on firm input sourcing under risk

Data

- Universe of firm-to firm transactions for a large Indian state
  - 3x Belgium, 7x Costa Rica, and 2x Chile.
- Unique origin/destination establishment identifier
- Value of transaction, 8-digit product code, quantity.
- Daily data from January 2018 to December 2020.

Figure: Stylized Example: Establishment-Level Network



- 53% of total purchases and 74% of sales are from within the state.
- We focus on the responses of firms in the network, not the network overall

Additional network stats

Climate Data

Figure: Monsoonal Rain Floods, 2018-2020

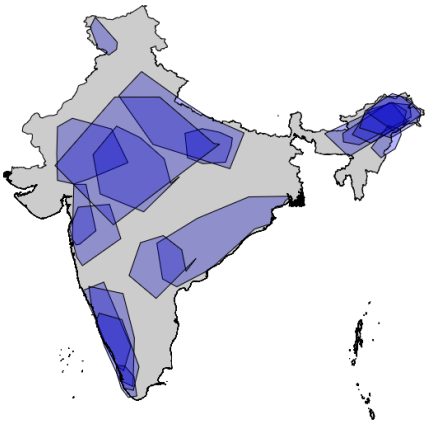


Table: Flood Summary Statistics

	All Floods Mean	Sample Floods Mean
Area (sq. km)	148,712.22	163,532.88
Dead	8.26	6.29
Displaced	59,445.26	33,908.57
N	19	7

- We use floods that are not in "our" state
- Stacked event study

Climate Supply Chain Specification

Supplier Climate Exposure:

$$\text{(Supplier Exposure)}_{j\tau} = \sum_{i}^{N} s_{i,j,\tau_0-1} \times 1\,\text{(Supplier } i \text{ exposed to flood in } \tau)$$

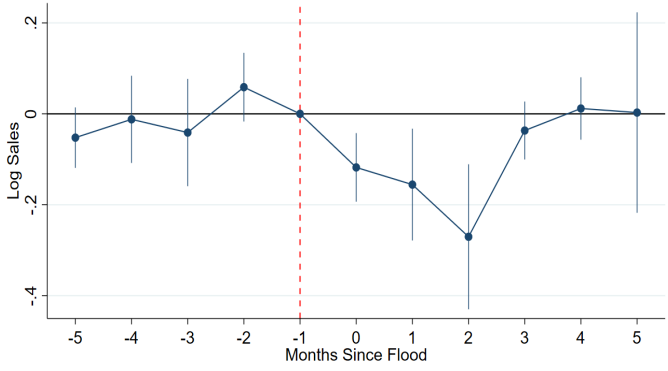
- s_{ij} = value of purchases that firm j buys from firm i, relative to firm j's total purchases

Estimation:

$$y_{j,t,k,\tau} = \sum_{x=-5}^{x=+5} \left[\gamma_x \,\text{(Supplier Exposure)}_{j\tau} + \delta_{\tau,x} + \beta_x X_{j,\tau_0-1}\right] + \delta_j + \delta_{r,k,t} + \epsilon_{j,t,k,\tau}$$

- $\delta_{\tau,x}$ = flood event-time since flood FE
- δ_j = firm FE
- $\delta_{r,k,t}$ = industry-region-time FE
- X_{j,τ_0-1} = log purchases in pre-period

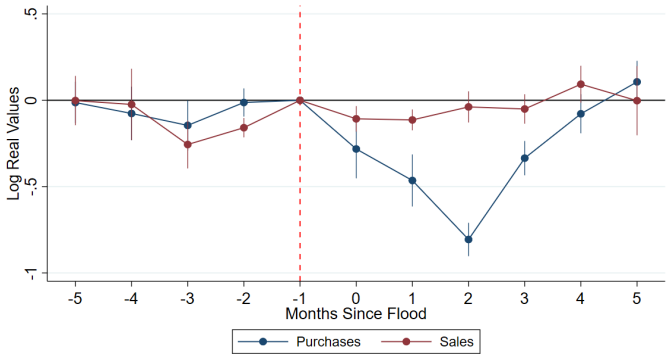
Sales of affected firms



Note. Includes firm, time, event-time, industry-real time, and log pre-period sales-time FEs. Standard errors clustered at the district level.

- Sales of affected firms in flood zones declines
- Specification: $y_{j,t,k,\tau} = \sum_{x=-5}^{x=+5}[\alpha_x 1\,(\text{Exposed to flood})_{j\tau} + \delta_{\tau,x} + \beta_x X_{j,\tau_0-1}] + \delta_j + \delta_{k,t} + \epsilon_{j,t,k,\tau}$

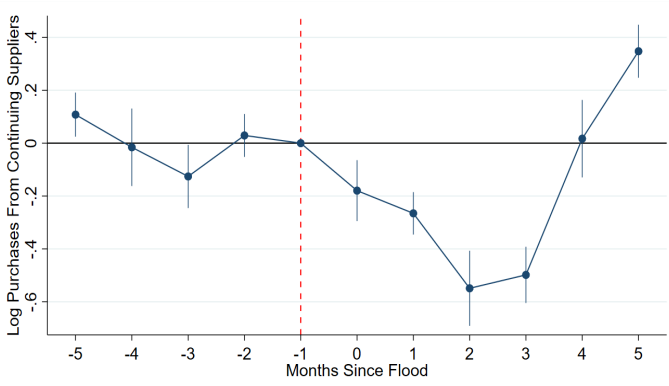
Purchases and Sales of Buyers



Note. Includes firm, time, event-time, industry-district-real time, demand controls and log pre-period purchases-time FEs. Standard errors clustered at the district level.

- Purchases fall but recover in 3-4 months, sales decline smaller

Purchases from Continuing Suppliers



Note. Includes firm, time, event-time, industry-district-real time, demand controls and log pre-period purchases-time FEs. Standard errors clustered at the district level.

- No new suppliers – purchases from old suppliers decline and recover New Suppliers
- Suggests firms already adapted to flood risk
- Product-firm level: similar patterns Product level Prices response

A Quantitative Model of Sourcing under Uncertainty

Environment

- Economy composed of I regions, endowed with L_i workers
- Two types of goods: non tradeable final goods and tradeable intermediates
- Final goods producers are monopolistically competitive
- Intermediate producers are competitive
- Iceberg trade costs of shipping intermediates across regions
- All firms within a region are homogeneous

Demand

- Consumers in each region i have Dixit-Stiglitz preferences over final goods:

$$U_i = \left(\int_{\omega \in [0,1]} q_i(\omega)^{\frac{\sigma-1}{\sigma}} d\omega \right)^{\frac{\sigma}{\sigma-1}}.$$

- Demand given by

$$q_i(\omega) = p_i(\omega)^{-\sigma} \mathbb{P}_i^{\sigma-1} Y_i$$

A Quantitative Model of Sourcing under Uncertainty

Production of Final Goods

- Final goods are produced using the following technology

$$q_i(\omega) = \phi_i \ell_i(\omega)^{\beta} X_i(\omega)^{1-\beta}$$

where ϕ_i is productivity, $\ell_i(\omega)$ is labor, and $X_i(\omega)$ is an aggregator of intermediates:

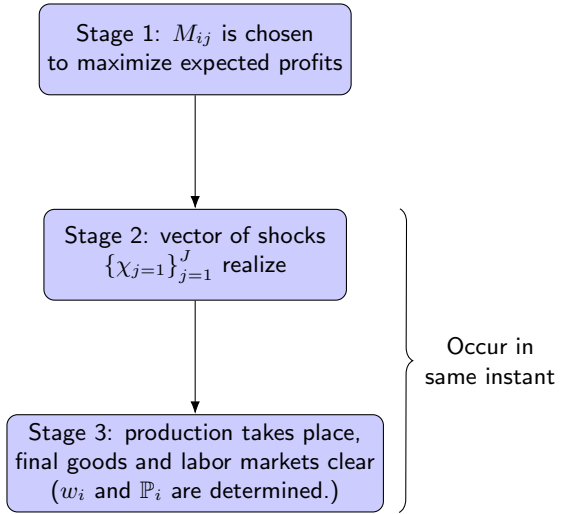
$$X_i(\omega) = \sum_{j \in I} x_{ij}$$

- Labor is a variable input
- Intermediates are quasi-fixed: $x_{ij} \leq \chi_j M_{ij} \quad \forall\ j$
  - M_{ij} is an input order fixed at the time of production
  - χ_j is an exogenous shock that is known at the time of production

Production of Intermediates

- Competitive suppliers using only labor with constant marginal cost $\frac{w_i}{z_i}$
- Iceberg trade cost τ_{ij}

Timeline


Stage 1: M_{ij} is chosen to maximize expected profits
Stage 2: vector of shocks $\{\chi_{j=1}\}_{j=1}^{J}$ realize
Stage 3: production takes place, final goods and labor markets clear (w_i and $\mathbb{P}_i$ are determined.)
Occur in same instant

Firm's Ex-Post Problem

Ex-Post, firms choose labor to maximize profits given M_{ij} and χ_j

Key Property: By monotonicity, $X_i(\omega) = \sum_{j \in I} \chi_j M_{ij}$

$$\max_{\ell_i} \left[Y_i \mathbb{P}_i^{\sigma-1} \right]^{\frac{1}{\sigma}} \left(\phi_i \ell_i^{\beta} \left(\sum_{j \in I} \chi_j M_{ij} \right)^{1-\beta} \right)^{\frac{\sigma-1}{\sigma}} - w_i \ell_i$$

Firm's Ex-Ante Problem

Ex-Ante, firms place orders to maximize expected profits minus *order* costs

$$\phi_i^{\sigma-1} \max_{M_{ij}\geq 0} \mathbb{E}_\chi \left(\kappa w_i^{\frac{\beta(1-\sigma)}{\beta+\sigma(1-\beta)}} \left[\left[Y_i \mathbb{P}_i^{\sigma-1} \right] \left(\sum_{j\in I} \chi_j M_{ij} \right)^{(1-\beta)(\sigma-1)} \right]^{\frac{1}{\beta+\sigma(1-\beta)}} - \sum_{j\in I} p_j^I M_{ij} \right)$$

where $\kappa = \left[\frac{\sigma(1-\beta)+\beta}{\beta(\sigma-1)} \right] \left[\frac{\beta(\sigma-1)}{\sigma} \right]^{\frac{\sigma}{\beta+\sigma(1-\beta)}}$.

Two remarks:

1. Only deterministic variable is ϕ_i
2. Equilibrium objects $\left\{ w_i, \mathbb{P}_i, Y_i, p_i^I \right\}_{i=1}^I$ are (potentially) stochastic since $\left\{ \chi_{j=1} \right\}_{j=1}^J$ are aggregate

Useful Properties

From the solution to the ex-post problem and the equilibrium conditions, it can be shown that:

1. Expenditure on orders in a given locations is equal to

$$\sum_j p_{ij}^I M_{ij} = \frac{(1-\beta)(\sigma-1)}{\sigma} Y_i$$

2. Aggregate profits in location (minus cost of orders) i are equal to

$$\hat{\Pi}_i(M) = \frac{1}{\sigma-1} w_i L_i$$

3. Labor demand by final goods' producers is a constant fraction β of the labor endowment, L_i
4. Aggregate income in location is is equal to

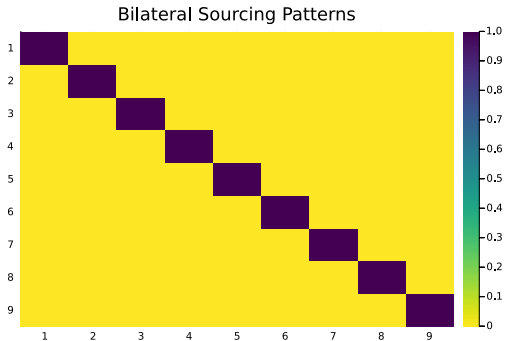
$$Y_i = w_i L_i + \frac{1}{\sigma-1} w_i L_i = \frac{\sigma}{\sigma-1} w_i L_i$$

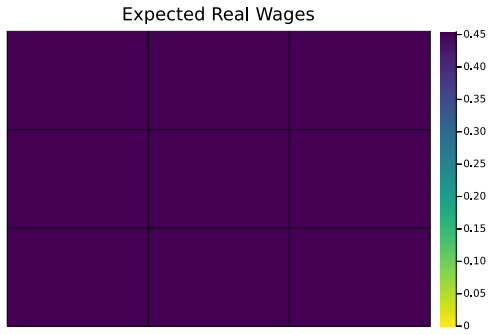
5. Wages adjust to ensure labor demand from intermediates producers is $(1-\beta)\, z_i L_i$

Comparative Statics: Setting

- 9 locations
- All regions are homogeneous in ϕ_i, L_i, z_i.
- Only differences come from the probabilities of the shocks, ρ_i
- Assume regions are in a 3×3 grid and that trade is costly and increasing in distance with elasticity 0.1
- If shock occurs, $\chi = 0.1$
- Five Experiments:
  1. No risk
  2. Homogeneous Risk, $\rho_i = 0.15$ for all i
  3. Heterogeneous Risk, $\frac{1}{I}\sum_{i=1}^{9} \rho_i = 0.15$
  4. Heterogeneous Risk and Autarky
  5. Heterogeneous Risk and Free Trade

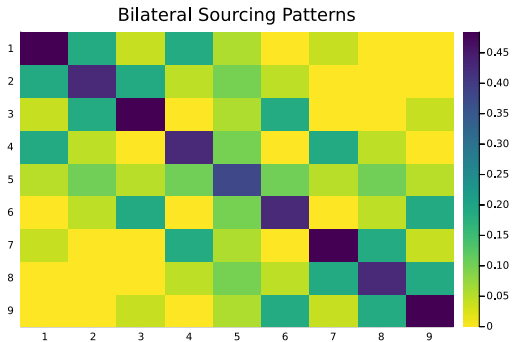
No Risk

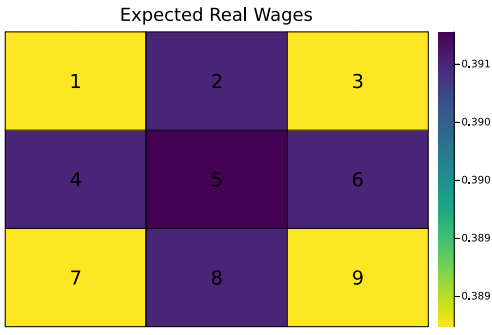




- Trade costs imply "own" sourcing share is 1
- Wages equalized across space (identical fundamentals)

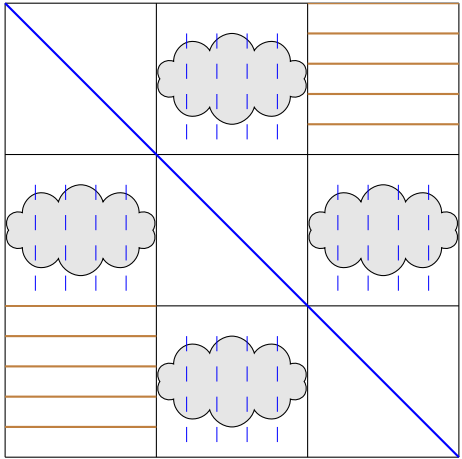
Homogeneous Risk





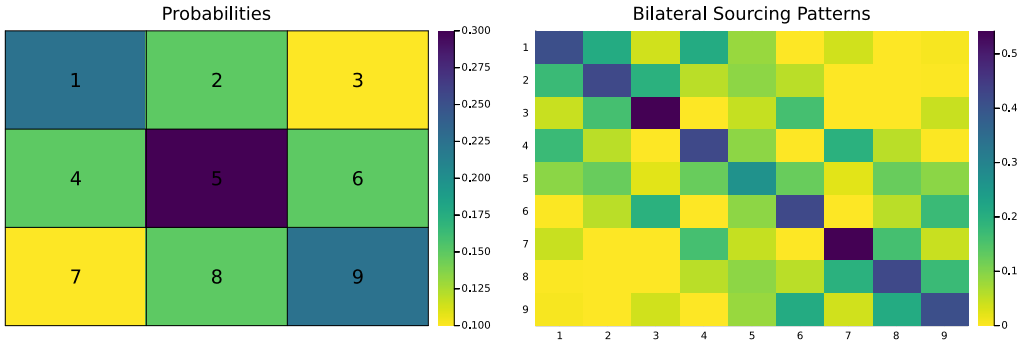
- Diversify by sourcing from "close" locations
- Real wages higher for more "central" regions

Geography of the Heterogeneous Risk



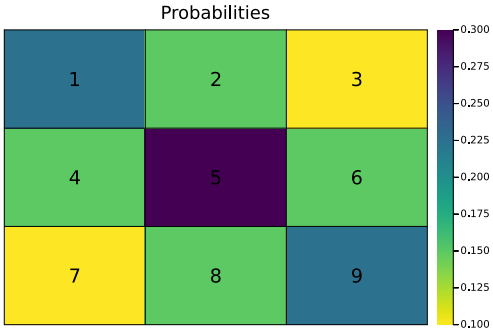
- Heterogeneous probabilities of floods across space

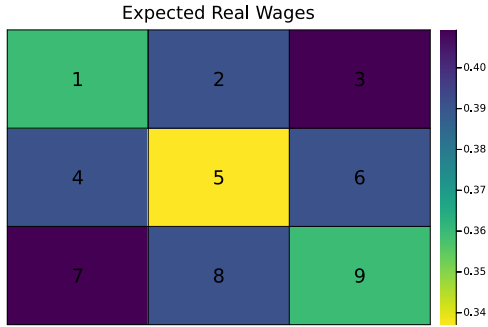
Heterogeneous Risk



- Heterogeneous probabilities of floods across space
- More variation in sourcing across space, some sourcing from risky locations too
- Tradeoff: climate risk vs increased costs (wages, trade costs)

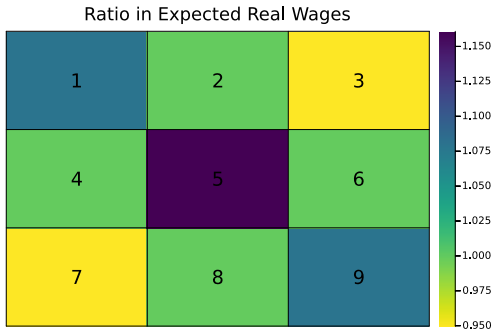
Heterogeneous Risk





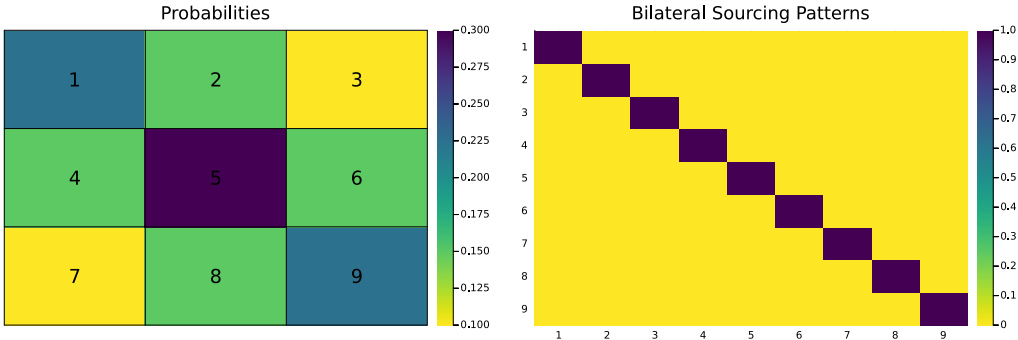
- Real wages highest in safest locations, despite no productivity differences
- Two channels: labor demand for "safer" inputs and lower price index of final goods

Welfare Comparison between Homogeneous and Heterogeneous Risk Cases



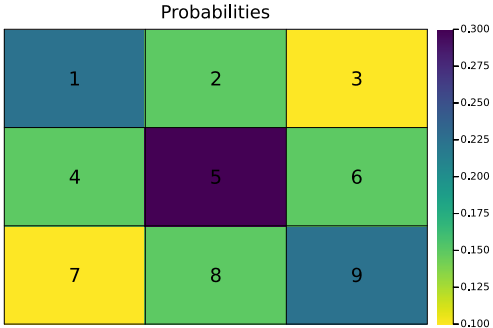
- Riskiest locations have lowest wages relative to homogenous case

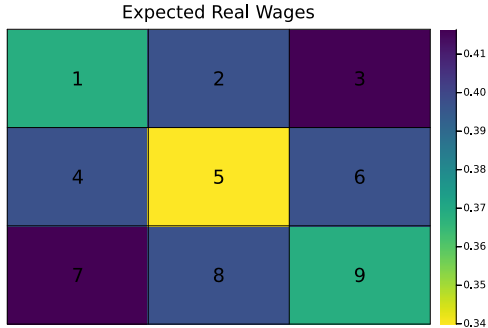
Heterogeneous Risk and Autarky



- Every firm in every region chooses same sourcing strategy, only intra-region sourcing.

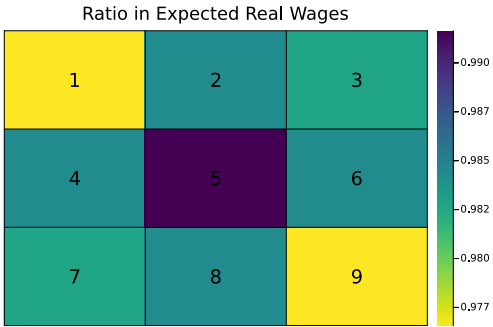
Heterogeneous Risk and Autarky

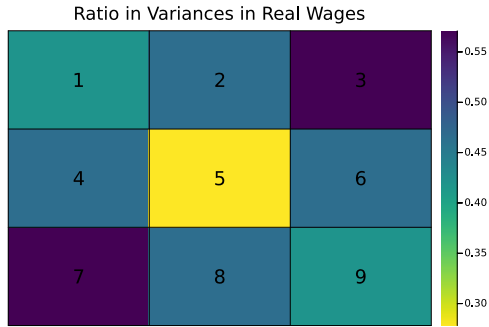




- No inter-regional sourcing, safest regions highest real wages

Welfare Comparison between Costly Trade and Autarky with Heterogeneous Risk Cases





- Same fundamentals across locations, no "gains from trade", only diversification $\longrightarrow$ real wages lower under trade
- Diversification benefits $\longrightarrow$ volatility of real wages lower under trade
- Free trade: Free Trade

Simple Calibration

Figure: Aggregate country to 20 regions

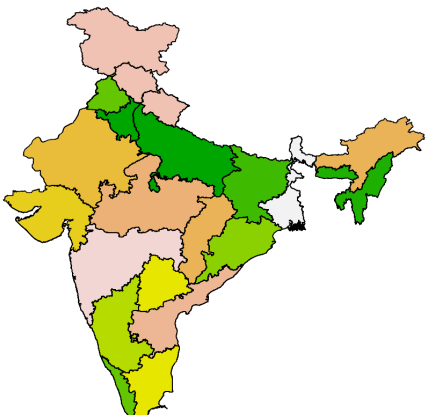


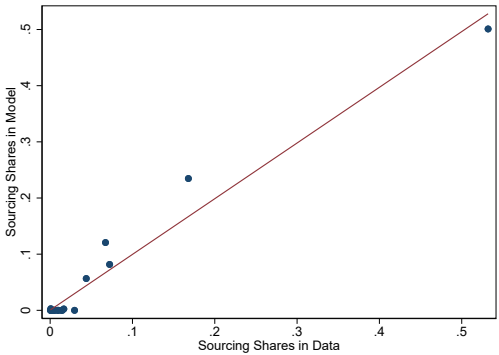
Table: Calibrated moments

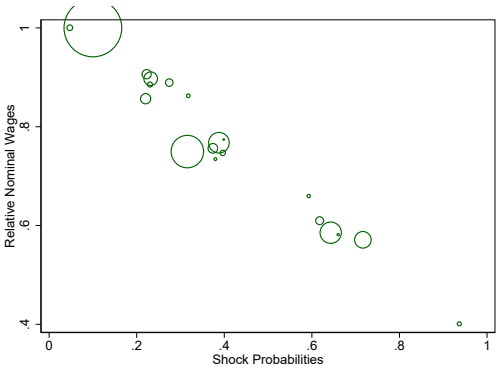
Parameter	Source
L_i: Labor endowments	Annual Survey of Industries (ASI), 2019-20
ϕ_i: Region productivities	Solow residual by industry (ASI, 2017-2019)
τ_{ij}: Iceberg Trade costs	Regression of within firm-product price on distance between buyer and seller (Transaction data)
ρ_i: Flood probabilities	Model inversion using trade shares across regions (Transaction data)
χ_i: Flood shock	Match drop of 75% in buyer purchases from event study (Transaction data)
β: Labor share	0.17: Expenditure in labor and capital to total sales (ASI, 2017-2019)
σ: Demand elasticity	2: Based on Boehm et al. (2023)

Calibration Results

Results so far....

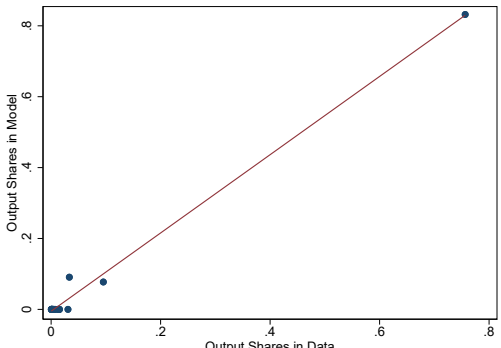
- Matching on sourcing shares across 20 regions (left panel)
- Higher shock probabilities, lower relative nominal wages (right panel)



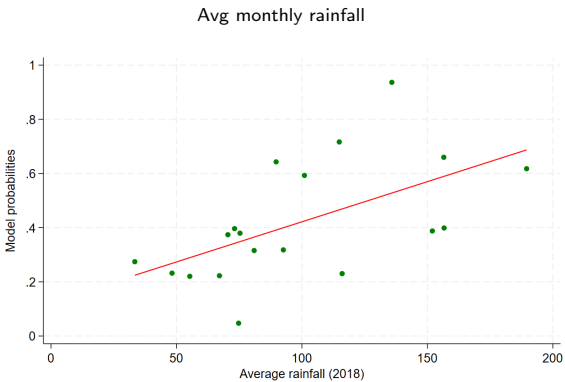


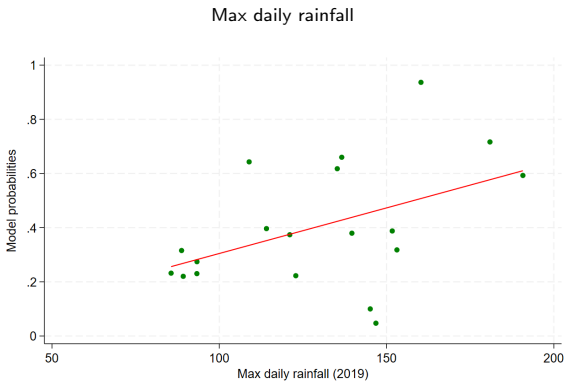
Results so far: Non-targeted moments

- Model fits non-targeted moments (sales shares) well



Quantitative results: model-implied regional risk



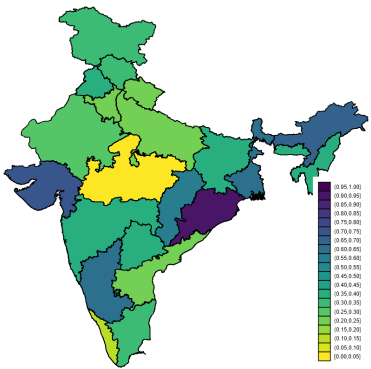


- Shock probabilities positively correlated with climate observables (correlation 0.56, 0.47)

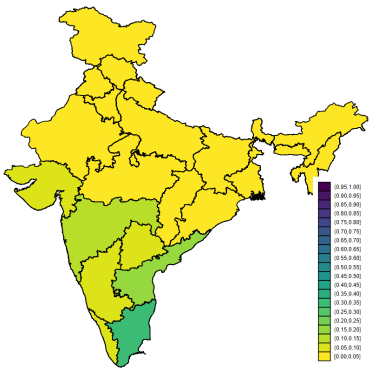
More variables

Quantitative Results: Probabilities and Sourcing Shares

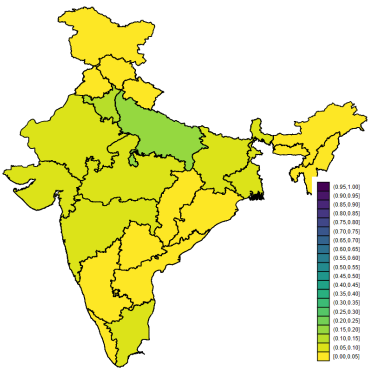
Shock Probabilities



Tamil Nadu Sourcing



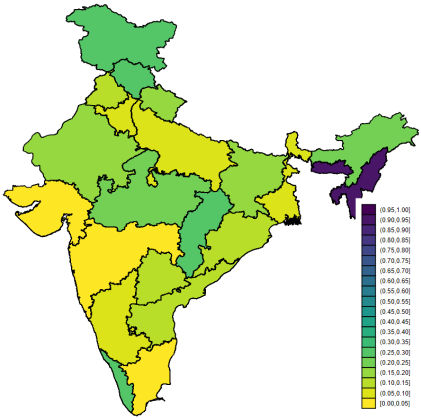
Uttar Pradesh Sourcing



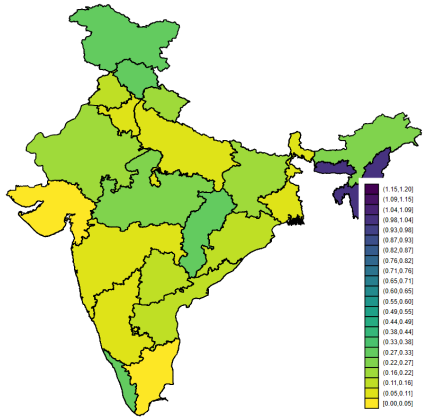
- Shock risk varies across regions
- Sourcing shares for Tamil Nadu and Uttar Pradesh vary based on probabilities and location

Quantitative Results: Expected Real Wages under Baseline and Autarky

Baseline



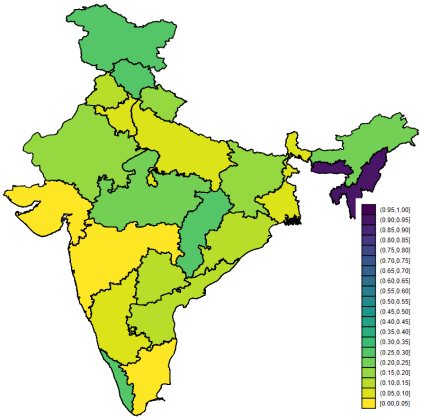
Autarky



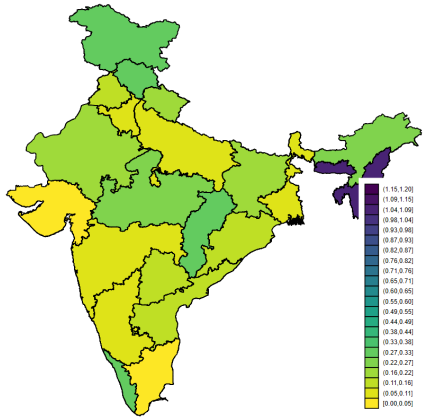
- Autarky: no interregional sourcing
- Expected real wages avg. 9% lower than in autarky, variance avg. 90% lower Variance

Quantitative Results: Expected Real Wages under Baseline and Free Trade

Baseline



Free Trade



- Free trade: eliminate trade costs between regions
- Expected real wages avg. 11% lower than in free trade, variance avg. 25% higher Variance

Discussion and Next Steps

- Climate-induced shocks and floods are likely to become more prevalent
  - If supply chains are affected, the impacts could be widespread
- Evidence suggests firms adapting sourcing strategies
  - Firms may have to trade off climate risk vs. increased costs (wage, trade costs)
- Findings so far
  - Model implied probabilities correlated with climate risk
  - Higher shock probabilities $\rightarrow$ lower wages
  - Diversification lowers volatility of real wages
- Implication: High-risk regions are likely to see larger declines in wages
- Next: more regions, input loop, inventories, aggregation, congestion externalities, planner's problem, climate projections, policy counterfactuals....

Thank you!

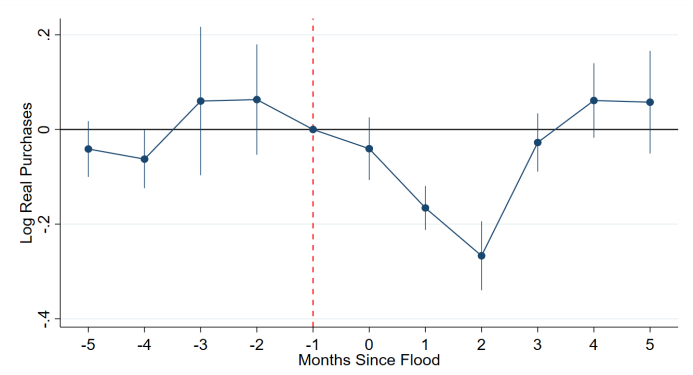
Describing the Network

Table: Network Characteristics

	Mean	p50	p10	p90
N suppliers per buyer	5.19	2.00	1.00	11.00
N products purchased	6.62	3.00	1.00	16.00
N buyers per supplier	5.71	2.00	1.00	11.00
Value of inputs purchased (millions of Rupees)	5.90	0.48	0.05	7.28
HHI products	0.65	0.62	0.23	1.00
Avg. HHI Sales	0.83	1.00	0.47	1.00
Indegree	0.93	0.11	0.00	2.05
Outdegree	1.10	0.13	0.00	1.88

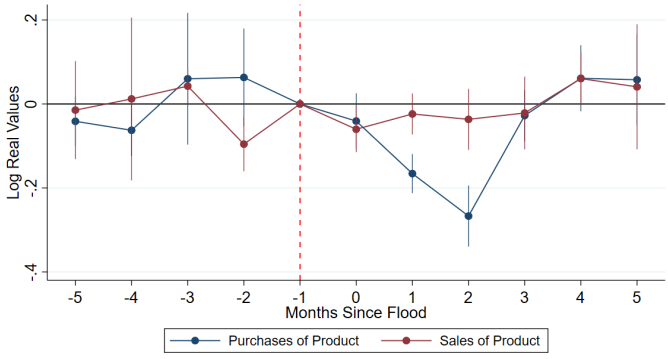
- We focus on the responses of firms in the network, not the network overall Back

Climate Results: Product-level purchases



Note. Includes firm-product, time, event-time, industry-product-district-real time, demand controls and log pre-period purchases-time FEs. Standard errors clustered at the district level.

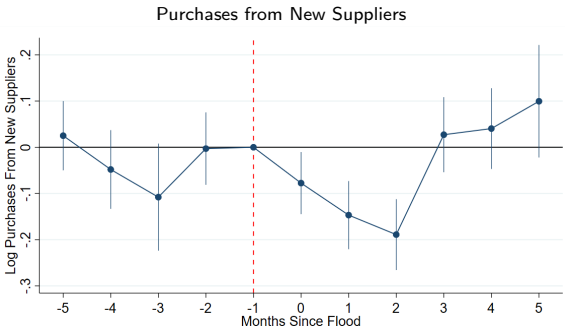
Climate Results: Product-level purchases and buyer product sales

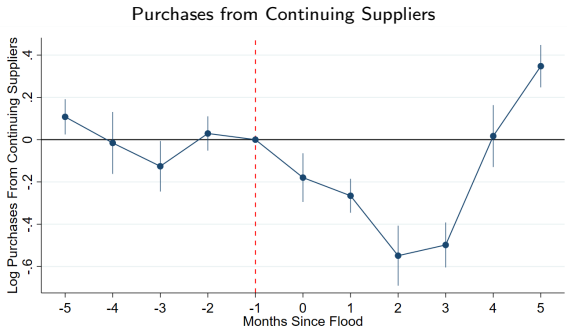


Note. Sales includes event-time, industry-district-product-time, firm-product, period t-1 log sales-time FE's. Standard errors clustered at the district level.

Back

Climate Results: Purchases

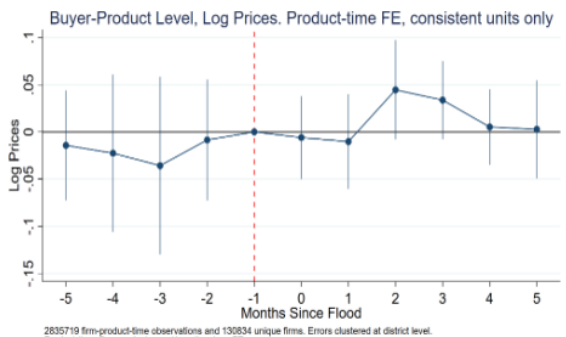




Note. Includes firm, time, event-time, industry-district-real time, demand controls and log pre-period purchases-time FEs. Standard errors clustered at the district level.

Back

Price Response to Floods



Back

Does Labor Market Clearing Imply Trade Balance?

Labor market clearing in each market j implies:

$$(1-\beta)L_i = \frac{Q_i^I}{z_i} = \sum_j \frac{\tau_{ij} M_{ij}}{z_i}$$

$$(1-\beta)w_i L_i = \sum_j \frac{\tau_{ij} w_i}{z_i} M_{ij} = \sum_j p_{ij} M_{ij} \quad \text{by ZPC of intermediate producers}$$

Trade Balance in each market j implies:

$$\sum_j p_{ij} M_{ij} = \sum_j p_{ji} M_{ji}$$

$$\sum_j p_{ij} M_{ij} = (1-\beta) w_i L_i \quad \text{by FOCs of final producers}$$

Variance in Welfare across Scenarios

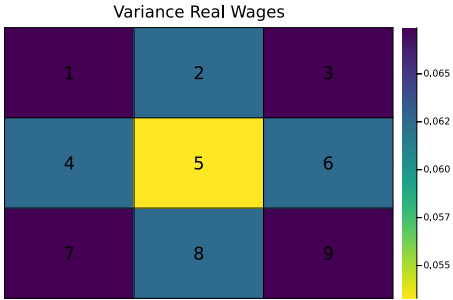


Figure: Homogeneous Risk

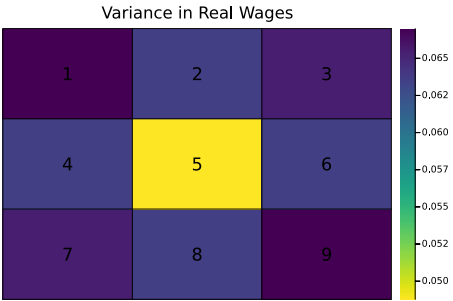


Figure: Heterogeneous Risk

Variance in Welfare across Scenarios

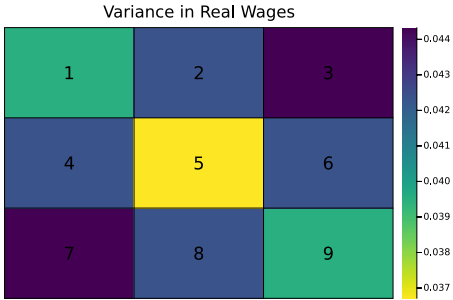


Figure: Heterogeneous Risk - Costly Trade

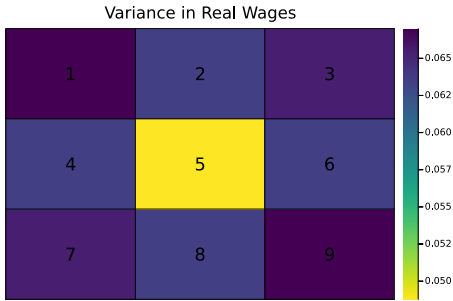


Figure: Heterogeneous Risk - Free Trade

Variance in Welfare across Scenarios

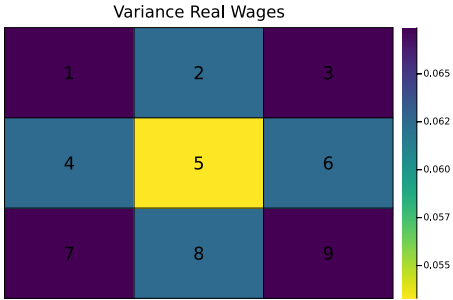


Figure: Homogeneous Risk

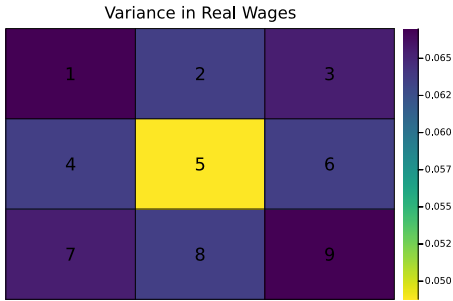


Figure: Heterogeneous Risk

Variance in Welfare across Scenarios

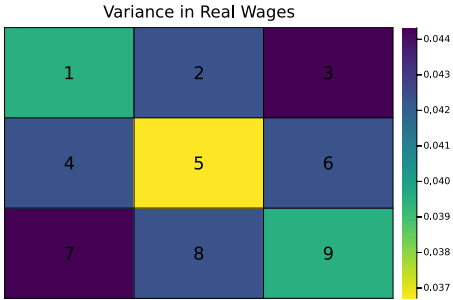


Figure: Heterogeneous Risk - Free Trade

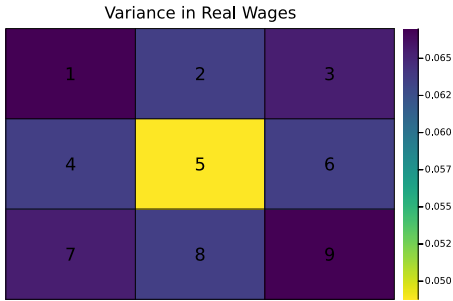


Figure: Heterogeneous Risk - Costly Trade

Variance in Welfare across Scenarios

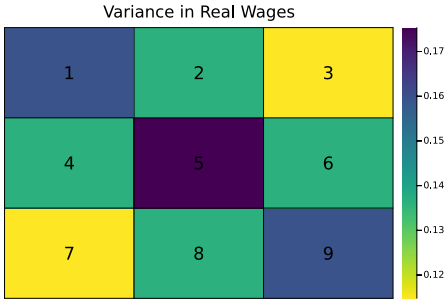


Figure: Heterogeneous Risk - Autarky

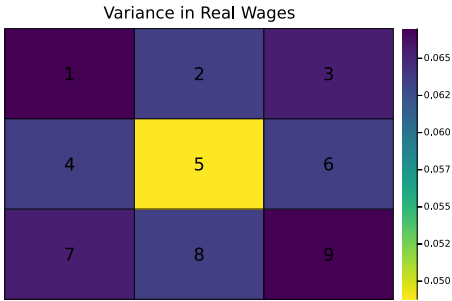
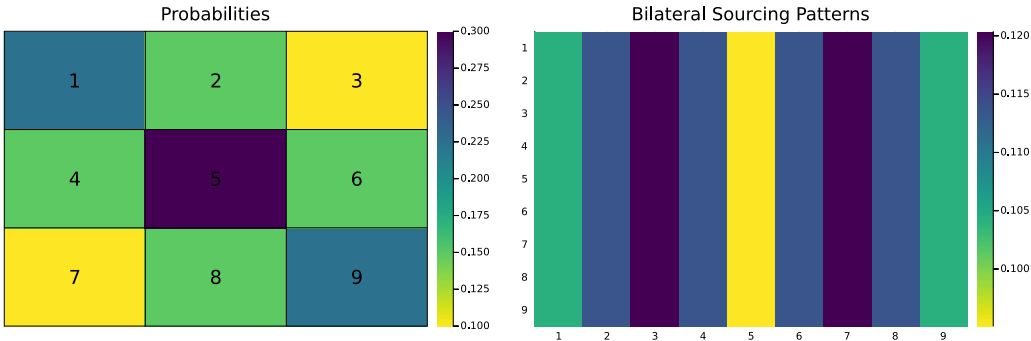


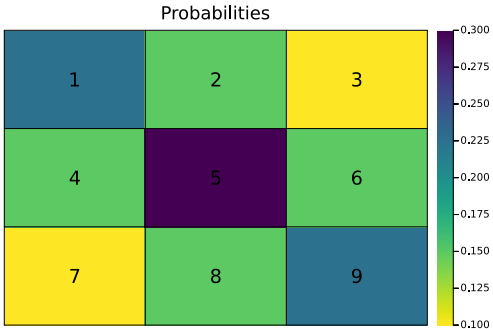
Figure: Heterogeneous Risk - Costly Trade

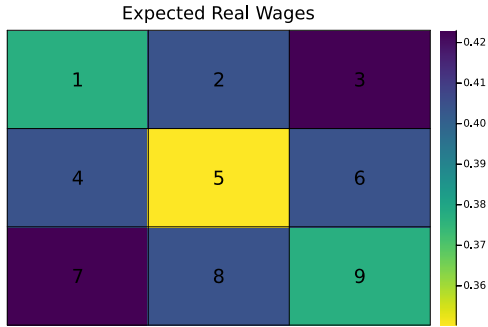
Heterogeneous Risk and Free Trade



- Every firm in every region chooses same sourcing strategy

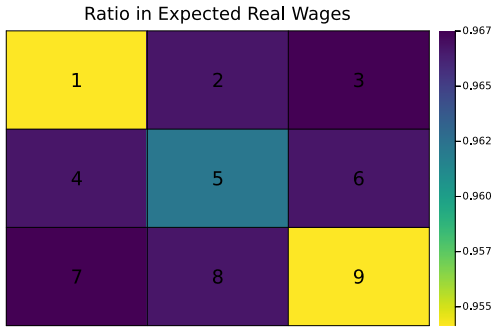
Heterogeneous Risk and Free Trade





- Increased real wage dispersion with heterogeneous shock probabilities

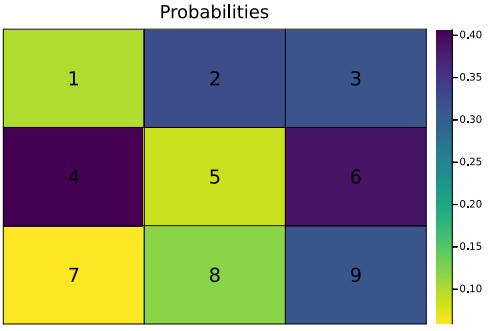
Welfare Comparison between Costly and Free Trade with Heterogeneous Risk Cases

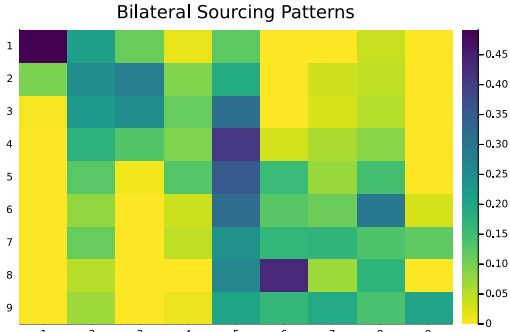


- Higher risk regions that are not geographically central see larger relative increases in expected real wages under free trade

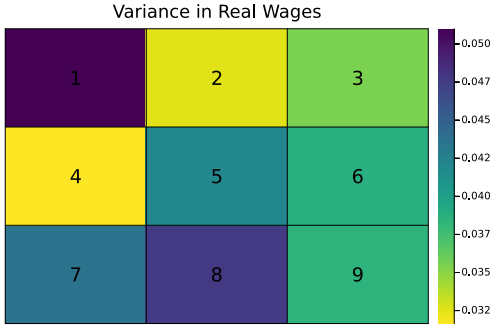
Back

Calibration



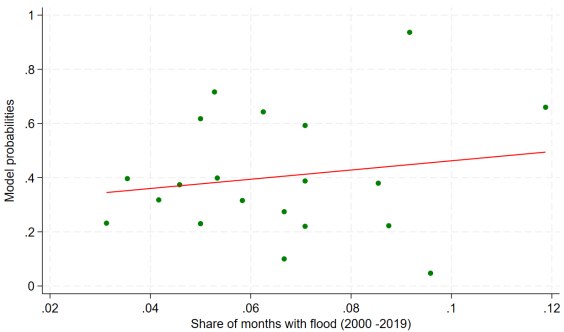


Calibration

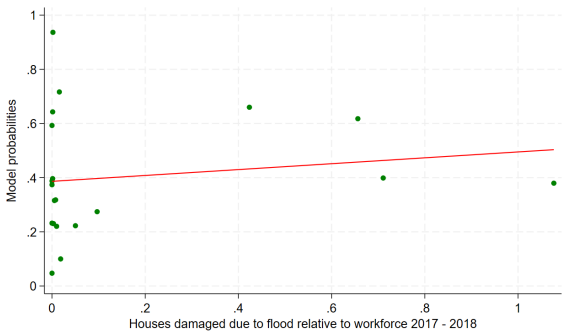


Shock probabilities are weakly positively correlated with climate observables

Share of months with flood (2000 - 2019)



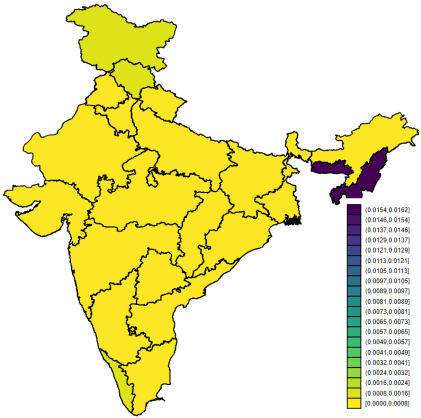
Houses damaged due to flood (rel to pop)



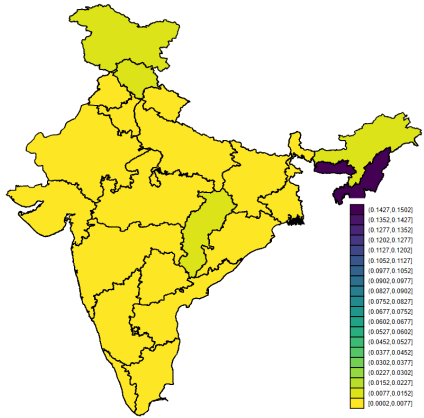
Back

Quantitative Results: Wage Variance under Baseline and Autarky

Baseline



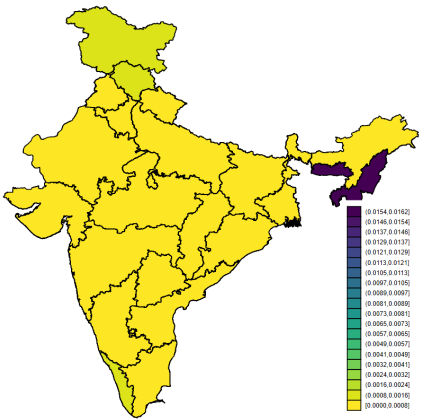
Autarky



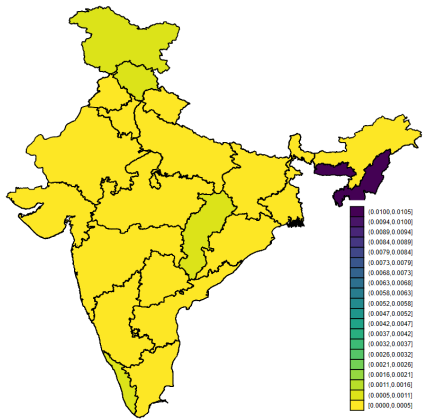
- Autarky: no interregional sourcing
- Variance of real wages avg. 90% lower than in autarky Back

Quantitative Results: Wage Variance under Baseline and Free Trade

Baseline



Free Trade



- Free trade: eliminate trade costs between regions
- Variance real wages avg. 25% larger than in free trade Back