Food Connections: International Trade, Extreme Events and Shock Propagation

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Global Trade Shocks and Geopolitical Uncertainty: Implications for Food Security in Emerging Economies

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Globalization of Food – Trade and Food Security

- over the last 40 years trade in agricultural goods has increased six-fold
- around 25% of agricultural production is shipped abroad

$\longrightarrow$ globalization of agriculture

What is the impact of trade on food security?

- risk diversification
- de-coupling population growth from availability of local resources

- exposure to shocks originating elsewhere
- dependence on other countries

$\longrightarrow$ use **network-based simulations** to address the issue

Methods

- simple **diffusion model** to simulate impact of local/global shocks to agricultural production
- **three main staples**: *Corn, Rice, Wheat* (more than 50% of global caloric intake)
- 3 weighted and directed networks of $\approx$ 150 countries connected by trade flows
- link weight = total calories embedded in trade flows
- investigate the impact of specific **shock scenarios**
  1. country-specific shock (*dust bowl* in the US)
  2. global food system shock (climate change)
  3. actual shock to validate the model (Ukraine war)

Baseline Model Setup

Model Summary

We model shock diffusion along the agricultural trade network as follows:

1. **Price Effect:** Production shock $\rightarrow$ global price increase
2. **Import Response:** Price hikes reduce import demand based on crop- and country-specific elasticities
3. **Export Reduction:** Countries limit exports to meet domestic needs
4. **Reserve Usage:** Reserves (50% of available stock) deployed to compensate lower import supply
5. **Consumption Impact:** Final absorption through reduced consumption

   Simulation stops when no country is able to further modify its trade flows to compensate for shortfall in food availability

Step 1: Global Price Effect of a Production Shortfall

- for every 1% loss in global Kcal from cereal staples (wheat, corn, rice, soybeans), global prices increase 7% for all commodities hit by the shock (taken from econ literature and recent work by World Food Program)
- price increase is assumed homogeneous across countries (global markets)

e.g. Ukraine shock: -4.75% Kcal (wheat + corn) $\Rightarrow +14.59\%$ price

$$\Delta p = 7 \times -\Delta Kcal \times \frac{p_{Wheat}+p_{Corn}+p_{Rice}+p_{Soybeans}}{p_{Wheat}+p_{Corn}}$$

- prices are in USD per Kcal
- the denominator includes only commodities hit by the shock

Step 2: Import Demand Response

- countries reduce their demand for imported staples according to country- and crop-specific elasticities
- available long-run elasticities divided by 20 to account for crisis conditions (limited ability to diversify away from specific products)
- average short-term elasticity: ≈ -0.04 consistent with existing studies (Roberts and Schlenker, 2009)
- for each country j and commodity c the new import level is:

$$\bar{M}_{jc} = M_{jc(t=0)} \times [1 + (\Delta p_c \times \varepsilon_{jc})]$$

- where $\varepsilon_{jc} < 0$ and $M_{jc(t=0)}$ represent pre-shock imports
- the price increase reduces demand and absorbs part of the shock

note: distributional effects of price increase not incorporated in the model

Step 3: Export Reduction as a Transmission Channel

- domestic absorption is given by the difference between production, net export and reserve usage
- $C_{jc} = Prod_{jc} - X_{jc} + M_{jc} + \Delta R_{jc}$
- at this step (t = 0), reserve usage is set to zero $\Delta R_{jc(t=0)} = 0$

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- at this step (t = 0), reserve usage is set to zero $\Delta R_{jc(t=0)} = 0$
- when the production shock is not compensated by a fall in import demand by trade partners, countries compensate by reducing exports

$$X_{jc(t+1)} = max\{X_{jc(t)} - dd_{jc(t)},\ 0\}$$

- with $dd_{jc(t)} = C_{jc(t=0)} - \left[Prod_{jc(t)} - X_{jc(t)} + M_{jc(t)} + \Delta R_{jc(t)}\right]$
- the reduction in exports is distributed across trade partners based on their relative GDP (size and purchasing power effect)

Step 4: Reserve Usage

- countries endowed with a certain amount of (country- and crop-specific) food reserves R_{jc}
- each country can use up to 50% of its initial stock of reserves to compensate for a shortfall in food availability
- *baseline model*: only reserves of the specific crop can be used
- $\Delta R_{jc} = R_{jc(t=0)} - \Delta M_{jc}$ subject to: $\Delta R_{jc} < 0.5 \times R_{jc(t=0)}$

- *extension*: when reserves are depleted, countries can tap into reserves of other crops $\longrightarrow$ this creates linkages across commodities
- the degree of substitutability depends on dietary diversity and is country-specific

Step 5: Shock Propagation and Final Adjustment

- export restrictions create a cascading effect through the network
- the simulation stops when no country can further reduce its exports or tap into reserves
- any demand deficit that cannot be propagated is then absorbed by reducing consumption
- at the end of the simulation we can compute the ultimate impact on caloric intake, food and nutrition security

Implementation

Data

- use bilateral trade data from FAO for 2016–2018 to build benchmark network (pre-shock reference point)
- convert quantity traded into Kcal using FAO conversion tables
- elasticities taken from Ghodsi et al. (2016)
- food prices, population and GDP taken from the World Bank

Descriptive Statistics

- we have 3 networks composed by 147/148 countries (nodes) and a number of bilateral links ranging from 1,765 (wheat) to 2,440 (rice)
- *density* (share of active over potential links) ranges from 8 to 11%
- around 1/3 of links are reciprocal
- diameter (shortest path length between most distant nodes) 6 or 7
- networks are (weakly) *disassortative*
- imports less concentrated than exports (more importers than exporters)

	Corn	Rice	Wheat		Corn	Rice	Wheat
nodes	147	148	147	in-centralization	0.23	0.21	0.19
edges	2129	2440	1765	out-centralization	0.72	0.81	0.64
density	9.9%	11.2%	8.2%	diameter	7	6	6
reciprocity	39.2%	32.5%	34.4%	assortativity	-0.17	-0.23	-0.22
median in-deg	13	14	11	median in-str*	445.35	255.49	1523.21
median out-deg	6	5.5	2	median out-str*	9.36	1.82	1.67

* million Kcal

Shock Scenario #1: US Dust Bowl

- “Dust Bowl” era (1930–1936) features three of six driest and hottest US growing seasons since the beginning of the 20th century
- likelihood of such events (historically $\approx 1:100$ years) could be reduced to $1:40$ years due to climate change
- despite advancements in farming practices, a 1936-style drought would still result in losses of about **-40% for corn**, **-30% for wheat** and **-20% of rice** in the **US** (Glotter and Elliot, 2016)
- US is a major wheat exporter (especially to developing countries) and accounts for about 35% of global corn exports

- shock hitting a single large exporter

Shock Scenario #2: Global Food System Shock

- we consider a severe global agricultural crisisscenario developed by Lloyd's in 2015
- the probability of such an event is estimated to be higher than 1 in 200 year (a common benchmark to define extreme events)
- the shock is triggered by a strong warm-phase El Niño Southern Oscillation (ENSO), which leads to **extreme weather events** (severe flooding and major droughts) and widespread **plant pathogen outbreaks** (in South America and Eurasia) across key food-producing regions
- the combined effects result in significant **global crop production decline** across several countries:

  -10% Corn
  -7% Wheat
  -7% Rice

Shock Scenario - Food System Shock

Corn:

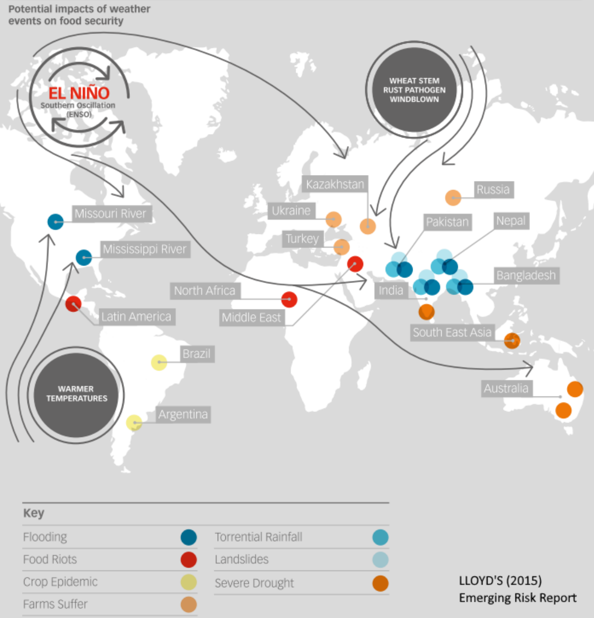
- US –27%

Wheat:

- US –7%
- India –16%
- Pakistan –15%
- Australia –50%
- Turkey –15%
- Kazakhstan –15%
- Ukraine –15%
- Russia –10%

Rice:

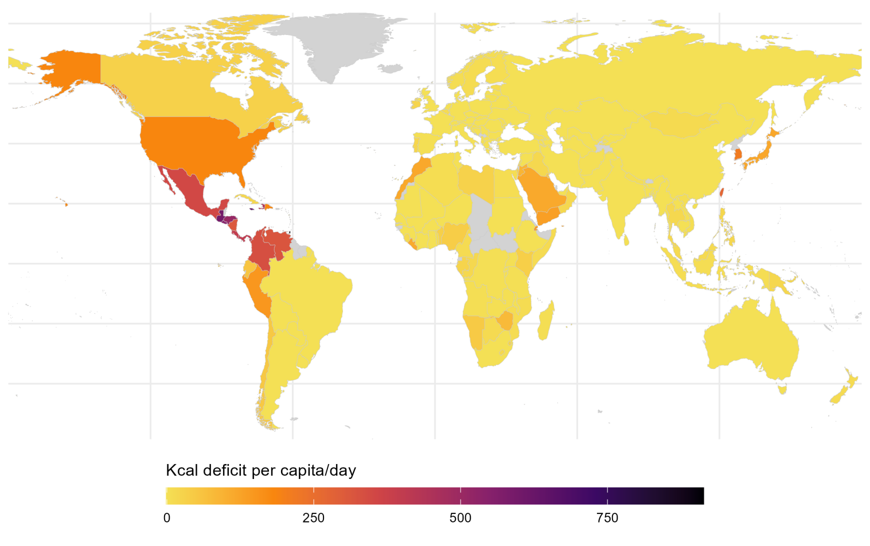
- India –18%
- Bangladesh –6%
- Indonesia –6%
- Vietnam –20%
- Thailand – 10%
- Philippines –10%



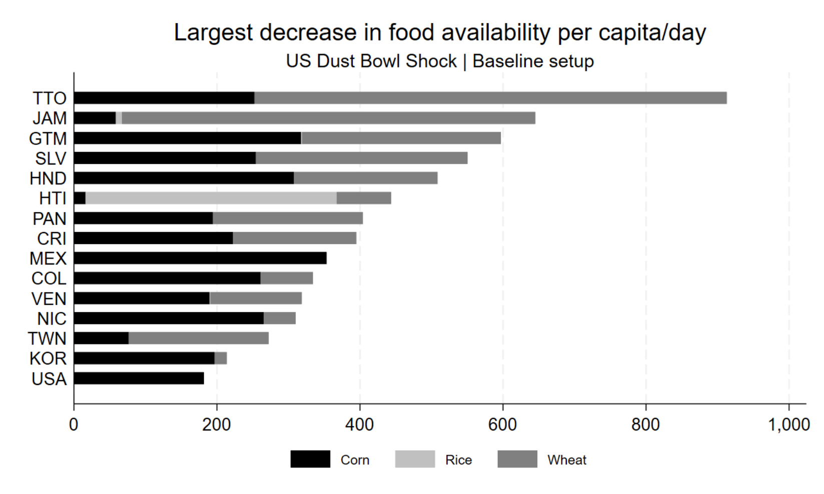
LLOYD'S (2015)
Emerging Risk Report

Simulation Results

Simulation Results - Dust Bowl Shock

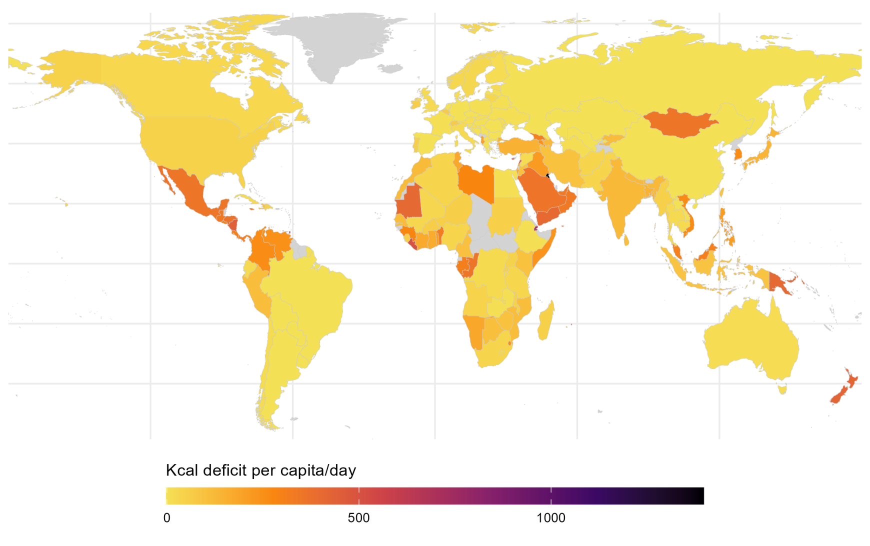


Most Severely Hit Countries - Dust Bowl Shock

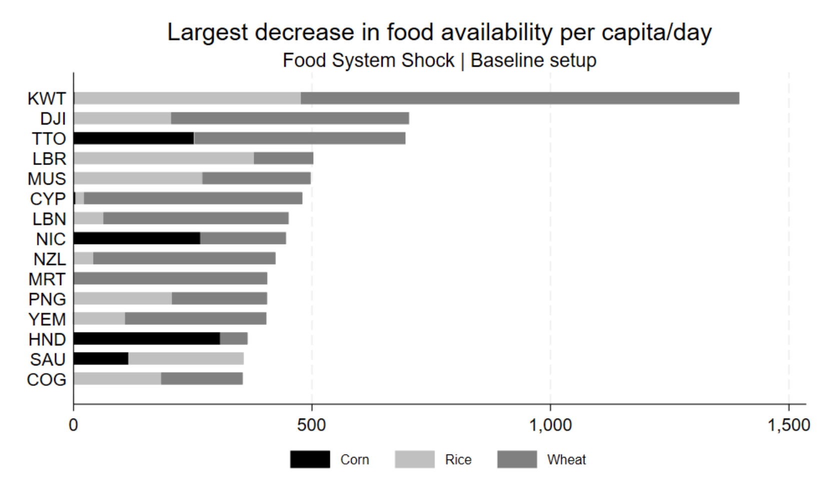


- 13 countries experience a decrease in food availability $>$ 250 kcal/per capita/day
- an additional 31.9 million people become undernourished

Simulation Results - Food System Shock



MOST SEVERELY HIT COUNTRIES - FOOD SYSTEM SHOCK



- 36 countries experience a decrease in food availability $>$ 250 kcal/per capita/day
- an additional 138.2 million people become undernourished

Descriptive Network Statistics

a) ***pre-shock*** *benchmark*

	Corn	Rice	Wheat		Corn	Rice	Wheat
nodes	147	148	147	in-centralization	0.230	0.214	0.185
edges	2129	2440	1765	out-centralization	0.716	0.806	0.644
density	9.9%	11.2%	8.2%	diameter	7	6	6
reciprocity	39.2%	32.5%	34.4%	assortativity	-0.165	-0.231	-0.217

b) ***Dust Bowl*** *shock*

	Corn	Rice	Wheat		Corn	Rice	Wheat
nodes	147	148	144	in-centralization	0.124	0.135	0.172
edges	1450	1659	1506	out-centralization	0.727	0.842	0.668
density	6.8%	7.6%	7.3%	diameter	6	5	6
reciprocity	25.4%	15.2%	28.3%	assortativity	-0.175	-0.233	-0.231

*c)****Food System*** *shock*

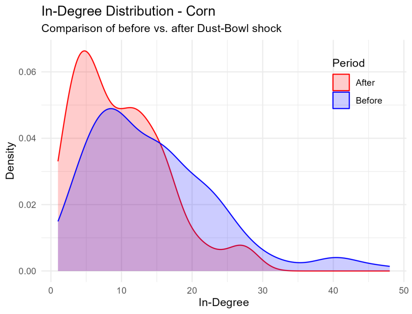
	Corn	Rice	Wheat		Corn	Rice	Wheat
nodes	147	148	140	in-centralization	0.124	0.105	0.159
edges	1449	1109	1112	out-centralization	0.716	0.806	0.644
density	6.8%	5.1%	5.7%	diameter	6	5	6
reciprocity	25.3%	12.8%	24.3%	assortativity	-0.176	-0.246	-0.219

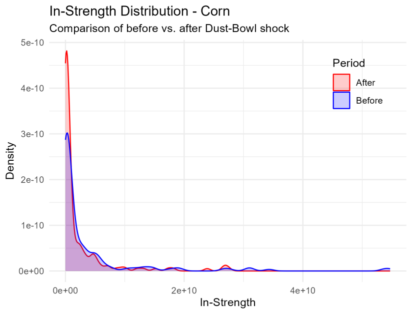
Reserve Usage

	Corn	Rice	Wheat
Dust Bowl shock:			
global reserve usage	-21.90%	-1.00%	-6.80%
countries with depleted reserves	46 (out of 117)	11 (out of 70)	39 (out of 127)
Food System shock:			
global reserve usage	-21.80%	-23.90%	-16.40%
countries with depleted reserves	46 (out of 117)	29 (out of 70)	74 (out of 127)

Impact on in-degree & in-strength distribution

Corn - Dust Bowl shock

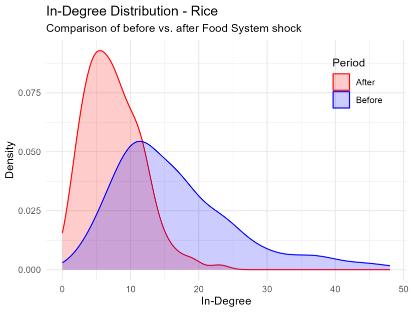


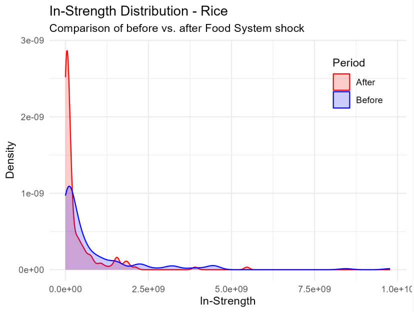


- shock has large impact on in-degree distribution (left panel) → 32% links dropped
- impact on in-strength distribution (right panel) weaker → mainly weak links that are dropped

Impact on in-degree & in-strength distribution

Rice - Food System shock





- 55% links dropped

OLS regression – Dust Bowl Shock

	Corn (1)	Rice (2)	Wheat (3)
Export degree (out)	33.195	-0.094	0.143
Import degree (in)	0.312	0.746	-1.401***
Food reserves (per capita)	0.042	-0.07	-0.152**
Export strength (per capita)	-0.012	0.015	-0.007
Import strength (per capita)	0.044**	0.049*	0.055***
Import concentration (C1)	46.525**	22.413	60.461**
Import from origin shock ($>$ 0.25)	105.223***	33.73	112.634***
GDP per capita (log)	-5.582*	-3.25	4.659
Observations	146	147	146
R-squared	0.55	0.17	0.37
F-statistic	12.14	1.19	2.58

Constant term non shown. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

- large importers tend to suffer larger deficits
- availability of (wheat) reserve stocks reduces the impact of the shock
- import diversification acts as a buffer

OLS regression – Food System shock

	Corn (1)	Rice (2)	Wheat (3)
Export degree (out)	-97.656	-0.385	-0.261
Import degree (in)	0.315	-0.531	-1.903
Food reserves (per capita)	0.038	-0.352	-0.425***
Export strength (per capita)	-0.011	-0.02	-0.016
Import strength (per capita)	0.044**	0.500***	0.161***
Import concentration (C1)	46.669**	62.527*	56.087
Import from origin shock (>0.25)	105.207***	40.853***	75.229***
GDP per capita (log)	-5.652*	6.236	19.586*
Production shock (dummy)		118.206***	41.597*
No. of observations	146	147	146
R-squared	0.55	0.51	0.33
F-statistic	6.22	8.28	4.74

Constant term non shown. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

- large importers tend to suffer larger deficits
- availability of (wheat) reserve stocks reduces the impact of the shock
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Extensions

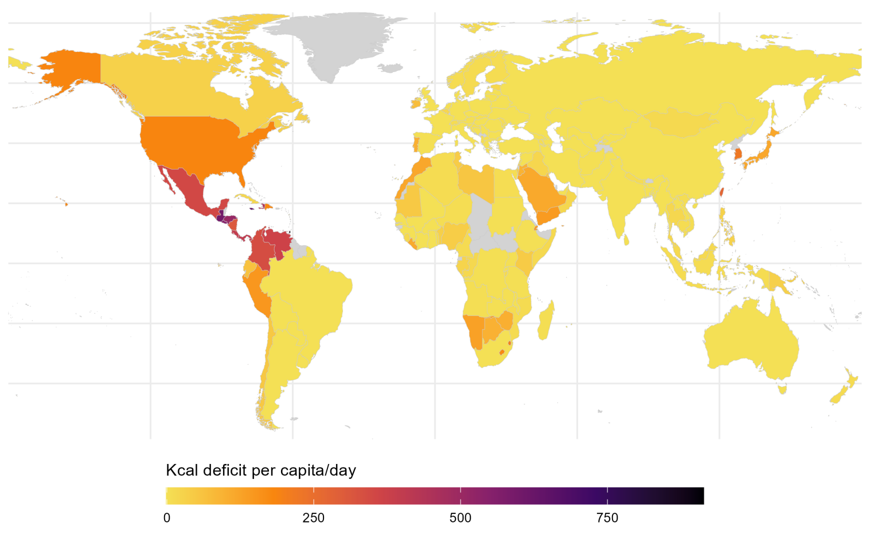
Extensions

1. Non-cooperative behavior
   - re-run the simulation **without** allowing countries to use **reserves**
   - reserve only used at the end of the simulation to compensate for existing deficits (cut exports *before* using reserves)

2. New link formation
   - countries not directly hit by the production shock use 10% of their reserves to activate new links
   - probability of new link established by means of a gravity model (cutoff at 50%)

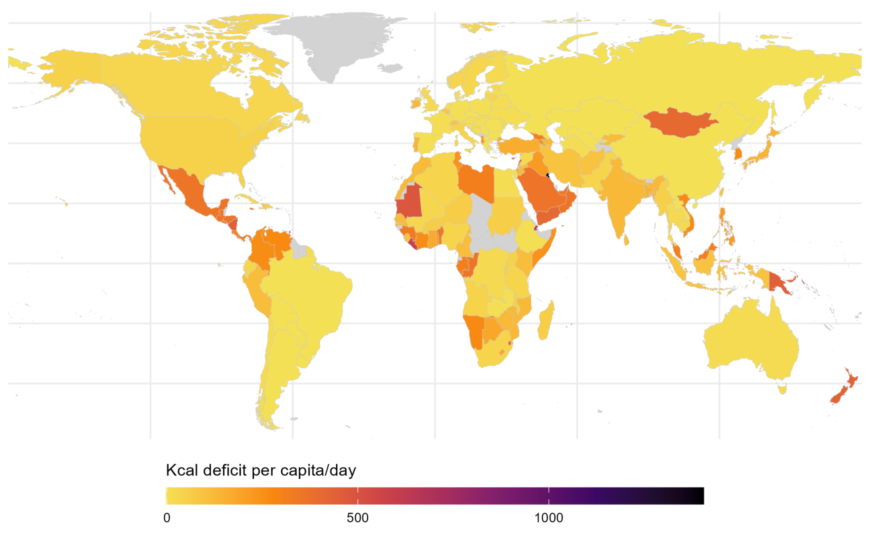
3. Multilayer network
   - allow for shock to one commodity to affect other products
   - when reserves of a specific commodity are depleted, countries use food reserves of other products according to a country-specific patterns of substitutability

Dust Bowl Shock | Non-cooperative setup



compared to the baseline setup **+3 million** people become undernourished

Food System Shock | Non-cooperative setup



compared to the baseline setup **+6.9 million** people become undernourished

New Link Formation

- use a *probit* model to estimate the likelihood of a trade link (corn, rice, wheat) among all country pairs, based on standard "gravity" variables:

$$\begin{aligned} LinkCrop_{ij} = & \beta_0 + \beta_1 \log(Distance_{ij}) + \beta_2 FTA_{ij} + \beta_3 EU_{ij} + \beta_4 ComLangEtno_{ij} + \\ & \beta_5 \log(Pop_i) + \beta_6 \log(Pop_j) + \beta_7 \log(GDP_i) + \beta_8 \log(GDP_j) + \\ & \beta_9 \log(CropProd_i) + \beta_{10} CropProdShare_i + \beta_{11} UNvote_i + \epsilon_{ij} \end{aligned}$$

- the model correctly classifies 90% of existing links
- a new link is activated if i) the estimated probability is above 0.5; ii) cereals import dependency of country $i < 0.4$; iii) country i is not directly hit by the production shock
- new export links are ranked according to their probability, and country i uses up to 10% of its reserve stocks
- between 51 (Dust Bowl - wheat) and 182 (corn) new links are created
- new links created before the shocks → comparative statics

Setup Comparison

Dust Bowl shock:

setup	avg deficit	median deficit	deficit 100	deficit 250	top 5 share	HHI	better	worse	additional undernour.
baseline	59.0	3.7	23	13	37%	0.046	–	–	31.9mil
non-coop	66.3	7.6	28	13	33%	0.039	0	59	34.8mil
new links	59.6	3.9	23	13	37%	0.046	3	18	31.9mil

Food System shock:

setup	avg deficit	median deficit	deficit > 100	deficit > 250	top 5 share	HHI	better	worse	additional undernour.
baseline	141.3	60.4	63	35	18%	0.019	–	–	138.2mil
non-coop	153.9	94.0	70	39	17%	0.017	0	101	145.2mil
new links	141.6	60.4	63	35	18%	0.018	10	26	138.8mil

- non-cooperative behavior significantly affects impact of shocks
- new link formation does not yield great benefit → review setup: more food available implies higher internal absorption
- when more countries are hit, the caloric deficit is (slightly) less concentrated

Open Issue: Model Validation

Model validation

Aim: Validate model accuracy by comparing simulation results with actual post-shock trade patterns

Case Study: Ukraine Production Shock (2021 $\rightarrow$ 2022)

Pre-Shock Trade Position (2021) as BAU scenario

commodity	production	exports	export share
Wheat	32.2M tons	18.8M tons	58%
Corn	42.1M tons	24.5M tons	58%

- **Wheat:** 36% decline (-11.5M tons from 32.2M tons)
- **Corn:** 38% decline (-15.9M tons from 42.1M tons)

Comparison: Simulation Vs. Actual Data

for how many countries/trade flows does the model correctly predicts a reduction?

- the ability of the model to replicate actual evolution of trade can be tested at the level of each **trade flow**, or aggregating **by country**
- set a minimum threshold to filter small prediction errors (10% or 25%)

share of correct predictions

	Corn		Wheat	
threshold	Countries	Trade Flows	Countries	Trade Flows
None	0.59	0.31	0.44	0.36
-10%	0.57	0.39	0.59	0.52
-25%	0.62	0.40	0.71	0.54

Comparison: Simulation Vs. Actual Data

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	Corn		**Wheat**	
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None	0.59	0.31	0.44	0.36
-10%	0.57	0.39	0.59	0.52
-25%	0.62	0.40	0.71	0.54

- aggregating at country levels substantially improves performance
- lack of a proper benchmark: what is “good” performance?


That's all Folks!

Supplementary Material

Price Effects

shock	Global Kcal shortfall	Price increase	Tot price effect
Lloyd's	-6.77%	47.41%	69.21%
Ukraine	-0.68%	4.75%	14.59%
Dust Bowl	-5.64%	39.48%	57.63%

Total price effect computed as: $\Delta P = 7 \cdot -\Delta Kcal \cdot \frac{\sum_c p_c}{\sum_{c,shock} p_{c,shock}}$, where p_c is the price of the different staple commodities (corn, rice, wheat and soybean) and $p_{c,shock}$ is the price of the commodities affected by the shock:

- LLoyd's: corn, rice, wheat
- Ukraine: corn and wheat
- Dust Bowl: corn, rice and wheat

Multi-layer Network

Aim: allow for shocks to one commodity to affect other products

- countries first use reserves of the crop that is affected by the decrease in production/imports (e.g. corn to compensate for a reduction in corn availability)
- when these reserves are depleted, countries can tap into food stocks of other commodities (if available), according to a specific *degree of substitutability* between crops in that country
- substitutability computed using actual data on food shares (from FAO Food Balance Sheets): substitution more likely when dietary diversity already high

details

- this mechanism creates a link across commodities: shock to one crop can impact other products (via absorption of reserves), although there is no *direct* shock transmission across commodities
- modeling issue: how do we deal with simultaneous shocks to different commodities? how are concurrent claims on reserves handled?

Setup Comparison: Newlinks - Baseline

Comparison of the setup with new links with respect to the baseline: number of countries with a caloric deficit smaller, equal or larger than in the baseline setup

	total caloric deficit		
shock	new links $<$ baseline	equal	new links > baseline
Dust Bowl	10	83	53
Food System	17	52	77

- the size of the difference is very small: median value = 0, values range between -17 and +29 Kcal/per capita/day (-16 to +14 in the Food System shock scenario)

Degree of Substitutability across Products

The degree of substitutability (DS) is computed as follows:

- for each country j and commodity pair (e.g., corn-wheat) compute the absolute differences (δ_j) between their shares (s_c) in the national food consumption (in kcal, per crop, per capita)
- $DS_{j,(corn-wheat)} = (1 - \delta_{j,(corn-wheat)})(1 - \max(\delta_j))\left(\frac{s_{corn}+s_{wheat}}{2/3}\right)$
- $DS_{j,(corn-rice)} = (1 - \delta_{j,(corn-rice)})(1 - \max(\delta_j))\left(\frac{s_{corn}+s_{rice}}{2/3}\right)$
- $DS_{j,(rice-wheat)} = (1 - \delta_{j,(rice-wheat)})(1 - \max(\delta_j))\left(\frac{s_{rice}+s_{wheat}}{2/3}\right)$
- DS ranges between 0 (low) and 1 (high);

e.g. corn 80%, rice 15%, wheat 5%

$DS_{j,(corn-rice)} = (1 - 0.65) \cdot (1 - 0.75) \cdot 0.95/(2/3) = 0.125$

$DS_{j,(corn-wheat)} = (1 - 0.75) \cdot (1 - 0.75) \cdot 0.95/(2/3) = 0.080$

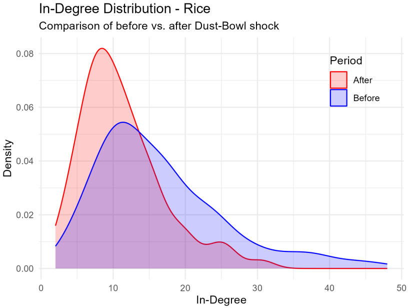
$DS_{j,(rice-wheat)} = (1 - 0.10) \cdot (1 - 0.75) \cdot 0.95/(2/3) = 0.068$

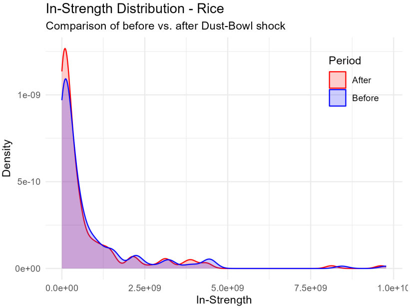
- the average DS across countries (in 2016–18) for corn-wheat is 0.21, for corn-rice is 0.20, and for rice-wheat is 0.26

back

Impact on in-degree & in-strength distribution

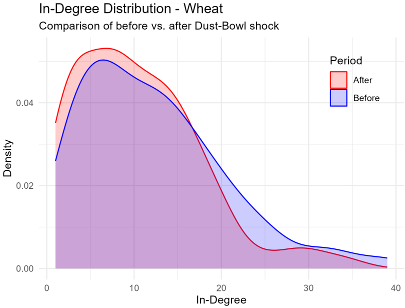
Rice - Dust Bowl shock

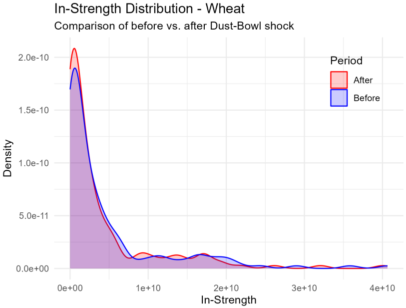




- 32% links dropped

Wheat - Dust Bowl shock

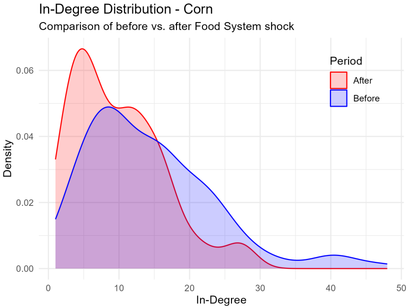


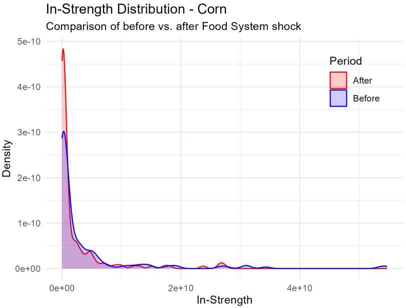


- more limited impact: 14% links dropped

Impact on in-degree & in-strength distribution

Corn - Food System shock

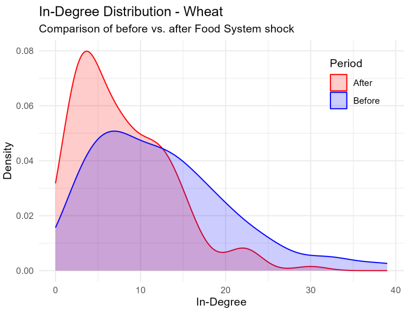


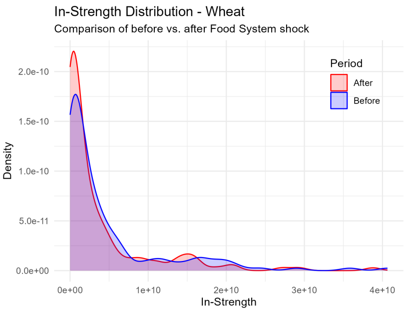


- 32% links dropped

Impact on in-degree & in-strength distribution

Wheat - Food System shock

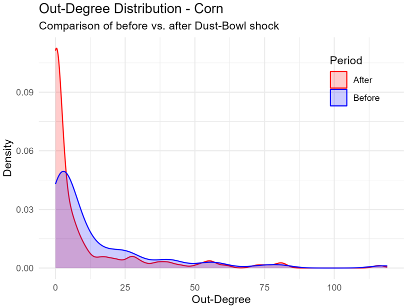


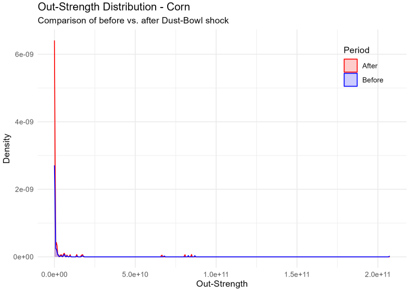


- 37% links dropped

Impact on out-degree & out-strength distribution

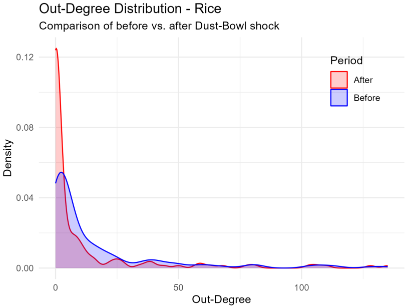
Corn - Dust Bowl shock

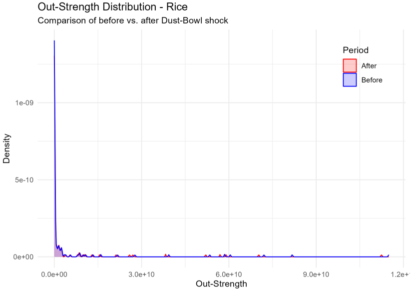




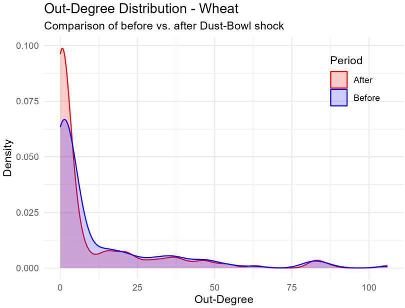
Impact on out-degree & out-strength distribution

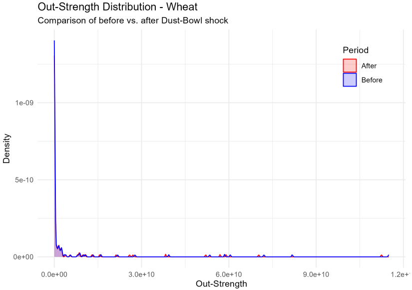
Rice - Dust Bowl shock





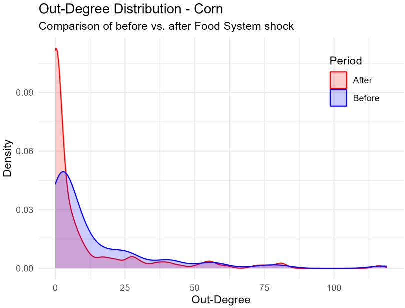
Wheat - Dust Bowl shock

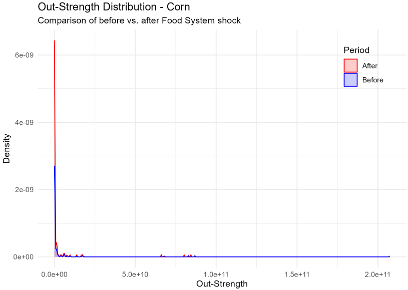




Impact on out-degree & out-strength distribution

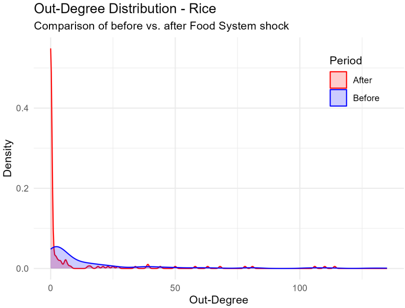
Corn - Food System shock

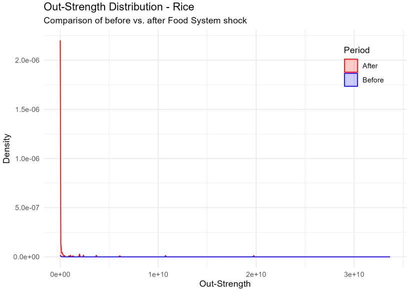




Impact on out-degree & out-strength distribution

Rice - Food System shock





Impact on out-degree & out-strength distribution

Wheat - Food System shock